Albert Einstein:
Physicist, Philosopher, Humanitarian

Parts I & II

Professor Don Howard

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Don Howard, Ph.D.

Professor of Philosophy, University of Notre Dame

Don Howard is Professor of Philosophy at the University of Notre Dame and Director of Notre Dame's Graduate Program in History and Philosophy of Science. In 1971 he graduated with high honor from Michigan State University's Honors College and its Lyman Briggs College, a one-of-a-kind residential science studies college, with a B.Sc. in Physical Science and a Physics concentration. Having been named both a Woodrow Wilson Fellow and a National Science Foundation Graduate Fellow, Professor Howard went on to earn first an M.A. (1973) and then a Ph.D. (1979) in Philosophy from Boston University, where he specialized in the Philosophy of Science. From 1978 through 1997, Professor Howard rose through the ranks from Assistant to full Professor in the Department of Philosophy at the University of Kentucky, which department he served as chair from 1993 to 1997. Since 1997, he has worked at the University of Notre Dame.

In 1980, Professor Howard was named a Fellow in Columbia University's Society of Fellows in the Humanities. In 1992, he was awarded a University Research Professorship by the University of Kentucky. He is now also a Fellow of the Center for Einstein Studies at Boston University; a Reilly Fellow in Notre Dame's Reilly Center for Science, Technology, and Values; and a Faculty Fellow in Notre Dame's Nanovic Institute for European Studies. In 2007, he was honored with election as a Fellow of the American Physical Society, a rare distinction for someone who is not, by profession, a physicist—this in recognition of his "ground-breaking studies of the interplay between physics and philosophy of science in the 20th century" and for his editorial and organizational work in "fostering the dialogue between physicists and philosophers and historians of science."

Albert Einstein has long been a major focus of Professor Howard's research. Professor Howard has served as an assistant editor and a contributing editor for the *Collected Papers of Albert Einstein*, as well as a consultant on several of the volumes of English translations that are published in tandem with the *Collected Papers*. Professor Howard is also a founding coeditor, along with John Stachel, of Birkhäuser's *Einstein Studies* series, which now comprises 11 volumes of scholarly work on Einstein and related topics. The author of many papers exploring diverse aspects of Einstein's philosophy of science and his physics, Professor Howard is now preparing a book on Einstein for the *Great Minds* series.

Professor Howard's research reaches into many other domains, among them the history of the philosophy of science, and science and religion. He has written extensively on the work of other prominent figures in physics, like Niels Bohr, Max Planck, and Erwin Schrödinger. In 1990, Professor Howard cofounded HOPOS—The International Society for the History of Philosophy of Science—which has since grown into a major international professional association. Highly in demand as a speaker, Professor Howard has lectured on a diverse array of topics at universities and conferences around the world and to groups such as the American Association for the Advancement of Science, the German Physical Society, and participants in the U.S. Department of Energy's annual National Science Bowl competition.

Professor Howard is also a dedicated classroom teacher and director of doctoral dissertations. In 2004, the University of Notre Dame recognized his many contributions to teaching with its Kaneb Teaching Award. Professor Howard teaches courses ranging from advanced graduate seminars on the foundations of quantum mechanics and space-time theory to introductory philosophy courses for undergraduates. One noteworthy course that Professor Howard regularly teaches, Philosophical Issues in Physics, is a rare example of a course offered jointly by a physics and a philosophy department and available for credit to undergraduate majors in both fields. Another one of Professor Howard's favorite offerings, Modern Physics and Moral Responsibility, invites students in all fields, but especially science and engineering majors, to reflect on the moral dimensions of the careers they are about to enter.

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Albert Einstein: Physicist, Philosopher, Humanitarian

Scope:

Albert Einstein was not just the 20th century's most brilliant and original physicist. He also played a major role in the development of philosophical understandings of science, and he was a tireless and highly visible advocate of peace and social justice. This course of lectures will present a kind of intellectual biography of Einstein. The biography—more complicated than some might think—will provide the framework, but along the way we will study his revolutionary innovations in physics, chiefly those in relativity and quantum physics, his philosophical reflections on the methods and foundations of the sciences as well as on ethics and religion, and his public efforts on behalf of causes like Zionism, civil rights, and the international control of atomic energy. We will try to understand what kind of world it was that produced an Albert Einstein and why intellectual and moral leaders of such stature are harder to find today.

Einstein would not have been Einstein without his many contributions to 20th-century physics. His most important ideas in the areas of quantum theory, relativity theory, and cosmology will be presented in a nontechnical way, emphasizing conceptual issues. The broader scientific background within which these ideas were born will be sketched, and later elaborations of Einstein's ideas will be outlined, especially in cosmology. We will ask why the Einstein who helped to discover the quantum theory later became its toughest critic. We will also look at how Einstein's unrealized dream of a unified field theory lives on today in the continuing quest for a "theory of everything" that would unify all of the fundamental forces of nature.

As we follow the development of Einstein's scientific ideas, we will pause along the way to note the distinctive manner in which Einstein's philosophical habit of mind made a difference in how he did physics. And we will look at some of the dramatic new perspectives in the philosophy of science that were in turn stimulated by Einstein's new physics, such as the philosophical movement known as logical positivism. Though Einstein became a staunch critic of logical positivism, it would be no exaggeration to say that he was one of the 20th century's most influential philosophers, as well as being its most influential physicist. He has as much to teach us about how science is done as about science itself.

Physics made Einstein famous, but from early on, Einstein deliberately used that fame to promote social and political causes about which he cared deeply. In the 1920s, it was mainly Zionism and pacifism. After moving permanently to the United States in 1933, Einstein took up such causes as racial equality and economic rights for working people. After World War II, he worked hard to promote the international control of atomic energy and to defend innocent targets of McCarthy era anti-communist persecution. When he urged President Roosevelt in 1939 to start work on the atomic bomb, Einstein the former pacifist thought that the production of atomic weapons was a necessary deterrent given the real possibility that Germany might develop the bomb first. But Einstein was horrified by the bomb's use against civilian targets in Japan and frightened by the Cold War arms race, which is why he devoted the last decade of his life to the cause of peace and international understanding.

The strongly moral public stance that Einstein took in advocating peace and justice contrasts strikingly with his private life. By his own admission, he did not treat his two wives well, a long history of extramarital affairs being only part of the problem. He had many close and lasting friends, but the challenge of personal moral responsibility was often too much to bear, leading him to seek a haven in the impersonal world of scientific truth. Ironically, some of the roots of Einstein's "cosmic religion" and his philosophy of nature might be found in the moral absolution afforded by a picture of nature as a realm in which all is strictly determined by rational scientific law—a realm in which neither chance nor free will has a place.

Einstein was many things. He was an inventor who held many patents. He was a musician who played the violin and loved Mozart. He was a personal friend of the Queen of Belgium and of the trash collector who picked up his garbage on Mercer Street in Princeton. He inaugurated the greatest revolution in the history of physics, but he liked to wear rumpled sweatshirts and no socks.

His fame is such that in the year 2000, *Time* magazine named Einstein its "Person of the Century." How did it happen that a physicist, of all people, became the most widely known and widely esteemed person in the world? What kind of world produced an Einstein, and what kind of world turned him into a hero and icon? How did his work come to influence the culture beyond physics, from art to morals? In learning the story of Einstein's life and work, we will learn much about ourselves as well.

Lecture One

The Precocious Young Einstein

Scope: We begin with a brief overview of the whole lecture series. Then we look at important events in Einstein's life up to the beginning of his university studies in 1896. Special attention will be given to the Einstein family's involvement in the "electro-technical" business, Einstein's schooling, his Jewish heritage, his decision to leave Germany and follow his family to Italy because of his dislike of German militarism, and his happy last year of high school in Switzerland. When the 17-year-old Einstein graduated from Aargau Cantonal School in 1896, the precocious but perhaps insecure adolescent had been transformed into a confident young man.

Outline

I. The aim of these lectures is to understand Einstein, the whole person and the whole thinker. Einstein the physicist cannot be understood without understanding Einstein the philosopher and Einstein the humanitarian. We begin with Einstein's early life and follow his path to his so-called *annus mirabilis.* In that "miracle year" of 1905, in the space of four months, the 26-year-old Swiss patent clerk published three revolutionary papers in the world's leading physics journal, the *Annalen der Physik* (*Annals of Physics*).

- **A.** The first, one of the most important papers in the history of the quantum theory, was the paper in which Einstein introduced the concept of the photon, the idea that light and other kinds of electromagnetic energy live in the form of discrete, particle-like quanta of energy.
- **B.** The second is less well known today, but it was equally important in its day. It concerns the seemingly erratic motion of tiny particles suspended in a fluid; we call this "Brownian motion."
- **C.** The third of Einstein's three miraculous papers was his most famous, the paper introducing the special theory of relativity.

II. Einstein was born on March 14, 1879, in Ulm, a middle-sized town in the German state of Württemberg.

- **A.** His parents, Hermann Einstein and Pauline Koch, were both descended from Jewish families with old and deep roots in that part of south-central Germany.
- **B.** German Jews had gained full civil rights and begun to move out of the ghetto into the mainstream of German life only a few decades earlier.
- **C.** Paths to many careers were still effectively blocked even for assimilating German Jews like Einstein's parents, so his father and uncle, Jakob Einstein, together founded a company in the field then called "electro-technology" and competed for contracts to "electrify" Germany's growing cities.

III. In 1880, when Einstein was one year old, the family moved to the Bavarian capital of Munich, where the new firm was located and initially prospered.

- **A.** The Einstein household was a cultivated one, in which learning was encouraged.
- **B.** For elementary school, Einstein was sent to the neighborhood Petersschule (St. Peter's School). Jewish religious instruction was provided at home, but the Einsteins were not strictly observant Jews.
- **C.** At age nine, Einstein graduated to the most prestigious humanistic high school in Munich, the Luitpold Gymnasium, where he was a respectable student.
- **D.** Much of Einstein's real education took place at home: It was at home that Einstein discovered what he called the "wonder" of Euclid's geometry at age 12; where he read the best popular scientific literature of the day; and where a young Jewish medical student, Max Talmey, introduced the adolescent Einstein to the works of the great German philosopher Immanuel Kant.
- **E.** Einstein grew up in intimate daily contact with the machinery of the new electrical age in the Einstein brothers' factory.
- **F.** He gradually developed an intense dislike of school, especially the militaristic discipline of the German schools.

IV. By 1984, a series of business reversals forced Hermann and Jakob Einstein to restart their business in the less competitive environment of northern Italy.

- **A.** Since Albert had barely a year of high school left, it was decided that he should stay behind, living with relatives. But Einstein's disaffection with school grew so great that, without consulting his parents, he dropped out and just showed up on the doorstep of the family's new Italian home.

B. Einstein took the entrance examination for one of Europe's preeminent technical universities, the Swiss Federal Polytechnic Institute (now commonly referred to by the initials of its German name as the ETH) and passed with flying colors in all technical subjects but failed in a few humanistic fields. Einstein so impressed the physicist on the examining committee, Heinrich Friedrich Weber, that he was invited to audit his lectures. But Einstein's parents decided instead to send him for one final year of high school at the famously progressive and liberal cantonal school in Aarau.

V. If high school in Munich had been hell, high school in Aarau was heaven. Einstein flourished in the free and stimulating intellectual and social environment.

- **A.** Einstein roomed with one of his teachers, Jost Winteler, whose daughter Marie became the first great love of Einstein's life. Though Albert and Marie soon went their separate ways, Einstein's bond to the Winteler family was so enduring that his sister, Maja, married Marie's brother, Paul, and Einstein's later best friend, Michele Besso, married Marie's sister Anna.
- **B.** In Aarau, it was not just Einstein the romantic who blossomed; it was also Einstein the physicist.
  1. During this time Einstein invented a thought experiment that convinced him that it would be physically impossible for a material system to move at the speed of light: What would one see if one could move alongside a light wave traveling at the speed of light? Since one would no longer see a passing train of wave crests and troughs, one would actually no longer see the light.
  2. The use of thought experiments became an essential part of Einstein's way of doing physics to the end of his life. He always thought about a physics problem first in terms of visual images and only later translated those pictures into a mathematical formalism.
- **C.** Einstein's year in Aarau produced a legend that he failed several subjects, including mathematics, but in fact his grades still placed him near the top of his class, where he had always been.
- **D.** It was during his Aarau year that hatred of German militarism led the willful Einstein, on his own initiative, to seek and win his release from German citizenship.

Suggested Reading:

Einstein, "Autobiographical Notes."

Howard and Stachel, *Einstein: The Formative Years*.

Isaacson, *Einstein: His Life and Universe*, chaps. 1–2.

Winteler-Einstein, "Albert Einstein—A Biographical Sketch."

Questions to Consider:

1. Think about the different educational philosophies that the young Einstein encountered in Munich and in Aarau. Does his experience suggest any lessons for how we educate children now?
2. To what extent should we regard the implications of a "thought experiment" in science as "evidence" constraining theory development?

Lecture Two

The Development of the Young Physicist

Scope: In this lecture we carry the story of Einstein's early life up to his "miracle year" of 1905, pausing to look at his university training at the ETH (the Swiss Federal Polytechnic Institute) in Zurich; his first loves; his illegitimate daughter, Lieserl; his marriage to fellow physics student Mileva Marić, Lieserl's mother; his fruitless search for a regular academic position; and his job at the Swiss Federal Patent Office in Bern. We consider what was distinctive about Einstein's training as a physicist. Of particular interest will be Einstein's less-than-dutiful attitude toward regular university instruction; his teaching himself the most important, cutting-edge science of his day through independent reading; and his deep engagement with the best work on the history and philosophy of science. Einstein's thinking was critically influenced by his reading of history and philosophy of science, as illustrated through the reading list of the "Olympia Academy," an informal discussion group that Einstein formed with a few like-minded friends in Bern.

Outline

I. In 1896 Einstein entered the ETH and chose physics as his major field. The same Heinrich Friedrich Weber whom Einstein had so impressed during the failed entrance examination became his major professor.

- **A.** Einstein's notebooks from Weber's introductory lectures still survive. Many of the topics covered by Weber would be recognized immediately by any first-year physics student today, but in other respects the lectures were old-fashioned. No mention was made of the new electrodynamics of James Clerk Maxwell.
- **B.** Perhaps it was the shortcomings of the physics available in the classroom that turned Einstein into a bad university student who cut classes in favor of spending his time in the library reading all of the best new physics literature.
- **C.** Einstein's physics education at the ETH included the history and philosophy of science. All physics students at ETH were then required to take a course in "The Theory of Scientific Thought" from neo-Kantian philosopher August Stadler. Einstein also signed up for Stadler's lectures on Kant, and on his own he read first-rate historical and philosophical works.

II. Physics was important for Einstein; so too, again, was romance. The ETH was where he met the second great love of his life and his future wife, Mileva Marić.

- **A.** Born and raised in the Serbian city of Novi Sad, Mileva had overcome huge obstacles to obtain a university education, first in medicine at the University of Zurich and then in physics at the ETH. Her combination of brains and beauty overwhelmed Einstein, and he fell head over heels in love.
- **B.** Albert and Mileva seem to have shared some of the bohemian attitudes then common in Zurich. Pacifists, socialists, modernists in the arts—even vegetarians were to be found in Zurich's many cafes and coffee houses. Albert was proud in 1901 to become a citizen of the Switzerland that was a tolerant home to such nonconformity, and he remained something of a bohemian to the end of his life.
- **C.** Albert and Mileva also shared a love of physics. Their letters are sprinkled with references to books and papers they were studying and to a few joint projects. Their shared love of physics was one of the most important factors drawing them together and keeping them together in the early years of their relationship.

III. Einstein graduated from the ETH in 1900. The normal next step for a promising young physicist was to secure a job as assistant to a senior physicist, but Einstein sought in vain for such a job, writing to just about every major physicist in every major university.

- **A.** There is some evidence that Einstein was now paying the price for not showing enough respect to his teacher Weber, who might well have been writing behind Einstein's back to torpedo his applications.
- **B.** Einstein was forced to settle for poorly paid, temporary teaching positions, but despite his lack of immediate professional success, his enthusiasm for physics continued unabated. In December 1900, he submitted to the *Annalen der Physik* the paper on capillarity that was to become his first scientific publication.

IV. As 1901 drew to a close, Einstein had more on his mind than his deteriorating financial and professional situation, for Mileva was now pregnant.

- **A.** Mileva had failed her ETH final examination for a second time in 1901, a development perhaps not unrelated to the pregnancy. Marriage was, for the time being, out of the question, largely because of opposition from Einstein's parents.

B. In spite of their problems, Albert and Mileva were clearly looking forward with joy to the birth of their daughter. Lieserl was born in January 1902, and they married a year later, after Einstein's dying father gave his blessing to the union. Two enduring mysteries are why they never brought their daughter to live with them and what eventually happened to her.

V. Late in 1901 Einstein was at last able to land a secure, reasonably well-paying job as a patent clerk in the Swiss Federal Patent Office.

A. One might think that such work would be poison to scientific creativity, but for Einstein it was just the opposite. Years later he looked back upon his seven years at the patent office as golden years in which, ironically, he had time to devote solely to physics.

B. Einstein built for himself in Bern a community of friends and colleagues who provided intellectual support.

1. Most importantly, he rounded up two new friends, Conrad Habicht and Maurice Solovine, to form a weekly reading and discussion group humorously named the "Olympia Academy." The list of their readings is dense with important books in the history and philosophy of science, including works by Ernst Mach, David Hume, John Stuart Mill, and Henri Poincaré.

2. Another important intellectual friend at this time was Michele Besso, whom Einstein had first met during his student days in Zurich and who was Einstein's closest intellectual friend to the end of his life. Besso is the only individual specifically credited with helping Einstein on the road to relativity.

C. Albert and Mileva settled into a comfortable domestic routine during at least the early years of their time in Bern. Their second child, Hans Albert, was born in 1904.

VI. The Olympia Academy was an important source of intellectual sustenance for Einstein. One of the few pieces of evidence bearing directly on the genesis of the papers that Einstein published in his "miracle year" is a letter that Einstein wrote to fellow academician Conrad Habicht announcing the papers' appearance and declaring the photon hypothesis paper—but not the relativity paper—to be "very revolutionary."

A. The Einstein who was about to publish such "revolutionary" new works was not the complete unknown that legend portrays. In fact, he had already published five quite respectable papers in the *Annalen der Physik*, the first back in 1901.

B. Still, he was only a clerk in a patent office, yet he had just inaugurated the greatest revolution in physics since the time of Newton. It could only have been done by a thinker who moved independently of the dominant currents of thought of his day.

Suggested Reading:

Einstein, "Autobiographical Notes."

Howard and Stachel, *Einstein: The Formative Years*.

Isaacson, *Einstein: His Life and Universe*, chaps. 3–4.

Overbye, *Einstein in Love.*

Renn and Schulmann, *Albert Einstein-Mileva Marić*.

Zackheim, *Einstein's Daughter*.

Questions to Consider:

1. How do we most fairly assess Mileva Marić's role in the development of Einstein's thinking about relativity, and how do we most fairly assess the impact of marriage to Einstein on her intellectual ambitions and goals for a career in science?
2. History and philosophy of science played a prominent role in Einstein's physics education and in his private study. Does his example suggest that these topics should be made a larger part of the training of young scientists today?

Lecture Three

The Birth of the Quantum Hypothesis

Scope: By his own account, Einstein's most "revolutionary" idea of 1905 was the photon hypothesis, the notion that light is not made up of continuously spreading electromagnetic waves but of discrete chunks of electromagnetic energy called "light quanta" or "photons." We examine the background to this radical new idea, most importantly Max Planck's proposal in 1900 of the "quantum hypothesis," the idea that matter and radiation exchange energy in discrete bits in phenomena such as "black-body radiation" (essentially the way the color of the light inside a black metal box changes as the box is heated). Einstein's highly original argument for the photon concept, which makes surprising use of the concept of entropy, is summarized, and we ponder Einstein's own immediate doubts about the universal validity of his photon hypothesis.

Outline

I. In addition to his papers on relativity and the quantum hypothesis, Einstein published in 1905 a significant paper on Brownian motion: the rapid, seemingly random motion of tiny particles like pollen grains suspended in a fluid like water. This paper was an achievement important enough to have made the career of any ordinary physicist. When his analysis was confirmed experimentally a couple of years later, it was seen as proof of the reality of invisible molecules and atoms.

II. Einstein's most revolutionary idea of 1905 was the photon hypothesis, the notion that light and other forms of electromagnetic radiation are not made up of continuously spreading electromagnetic waves but of discrete chunks of electromagnetic energy called "light quanta" or "photons."

III. In the late 1890s, when Einstein was a student at the Polytechnic in Zurich, the physics community was nearly unanimous in believing that we were on the verge of achieving a complete understanding of the physical universe.

- **A.** It was thought that all of the known, fundamental forces—gravity, electricity, and magnetism—had been explained. Everyone expected that mechanics, electrodynamics, and the molecular-kinetic theory of heat would soon be unified in one grand theory of everything.
- **B.** Some curious anomalies had recently been uncovered, but very few people suspected that those anomalies contained within them the seeds of the greatest revolution in physics since the time of Newton, over 200 years earlier.

IV. Faith in an imminent unification of physics was strengthened by steady progress in both theory and experiment. Mechanics, electrodynamics, and the molecular-kinetic theory of heat all agreed on three deep and important fundamental principles.

- **A.** An essential assumption of all classical physics was determinism, which is the idea that the future course of physical events is fixed down to the smallest detail by past causes.
- **B.** Equally fundamental was the assumption that all physical processes were continuous, in the sense that all changes in nature could be analyzed in terms of continuous sequences of ever-smaller changes, with no gaps or jumps.
- **C.** A third fundamental feature of classical physics was the principle of separability, which asserts that the physical state of any composite system is simply the aggregate of the separate states of the individual components: The state of each of those individual components is what it is independently of the states of the other components.

V. The quantum revolution began in 1900, when Max Planck first introduced the idea of "energy quantization" to explain the energy spectrum of so-called black-body radiation.

- **A.** The problem is, essentially, describing and explaining how the frequency (color) of electromagnetic radiation inside a black box changes as the box is heated. The empirical law had been determined with great accuracy by careful experiments, but attempts to explain that empirical law theoretically had failed.
- **B.** A straightforward analysis based on the principles of Maxwellian electrodynamics yielded a formula that fits well the low-frequency end of the black-body spectrum. An equally straightforward analysis based on the principles of mechanics and the kinetic theory yielded a formula that fits well the high-frequency end of the spectrum. But no one could give a theoretical analysis yielding a curve fitting well the whole spectrum.
- **C.** Planck found a single formula that fit the empirical spectrum perfectly and contained the two separate formulas as, respectively, the low-energy and high-energy limits. He noticed he could derive the hybrid formula by changing one of the crucial assumptions of classical physics, namely, that when the molecules in the walls of the box emitted or absorbed radiation they did so not continuously but in discrete units or quanta of energy.
- **D.** Neither mechanics nor electrodynamics allowed for the discontinuous exchange of energy. But the Planck formula worked, so it was assumed that it had to be pointing physicists toward some new, deep insight.

VI. It was Einstein who in 1905 would first begin to reveal the deep truth about the new quantum realm with his even more radical explanation of the photoelectric effect.

A. It was known that light falling on a metallic conductor could create an electrical current by knocking electrons out of the metal. Classical electrodynamics predicted that the energy of those electrons would be proportional to the intensity of the light, but experiment had shown that the electron's energy was proportional, instead, to the frequency of the light.

B. Einstein started by thinking not about the energy of the emitted electrons or the frequency or intensity of the light, but about the entropy of the light. He made a bold conjecture: If the entropy of a gas and the entropy of high-frequency radiation obey the same kind of formula, then just as a gas consists of lots of tiny, mutually independent, billiard-ball-like molecules, so too, high-frequency radiation must consist of lots of tiny, mutually independent bits or quanta of electromagnetic energy.

C. Planck had already proposed that when matter emits or absorbs radiation, it does so in discrete amounts. Einstein was now proposing that high-frequency radiation always exists in the form of independent, discrete quanta of energy (photons). Einstein easily showed that the energy of the electrons emitted in the photoelectric effect was proportional to the frequency of the radiation, not its intensity, simply because quanta of higher frequency carried more energy.

VII. A measure of how radical Einstein's light quantum (or photon) hypothesis was is that it took more than 20 years for it to be accepted even by such famous champions of the quantum theory as Niels Bohr, the inventor of the quantum model of the atom in 1913.

A. Einstein, too, had doubts, which he expressed publicly within a few years. The corpuscular analogy works only in the limit of infinitely high frequencies; in that limit it is "as if" radiation had a granular structure. In fact, radiation of all frequencies has a sort of chameleon-like nature. The higher the frequency, the more it behaves like a radiation gas made up of mutually independent quanta. But the lower the frequency, the more it behaves as if its constituent bits were not mutually independent.

B. Thus, radiation must have a dual nature, both wavelike and particle-like. Inasmuch as its constituents are not mutually independent, radiation behaves like waves that are capable of interfering with one another. Inasmuch as radiation's constituent bits are mutually independent, radiation behaves like a classical Boltzmann gas.

C. Here was the first hint of another deep truth about the quantum realm, something that we now call "entanglement." And here Einstein confronted a violation of the third of the deep principles of classical physics, the principle of separability.

Suggested Reading:

Bernstein, *Secrets of the Old One*.

Einstein and Infeld, *The Evolution of Physics*.

Jammer, *The Conceptual Development of Quantum Mechanics*.

Kragh, *Quantum Generations*.

Pais, *"Subtle is the Lord …"*

Stachel, *Einstein's Miraculous Year*, pt. 4.

Questions to Consider:

1. Some argue that determinism is necessary in science, because if we can't explain exactly why, how, and when physical events occur then we haven't really understood them. Do you agree?
2. In 1909 Einstein first explicitly hinted at the idea of wave-particle duality. Does it make sense to represent fundamental physical entities in such a two-faced way, or must science always give a completely univocal description of reality?

Lecture Four

Background to Special Relativity

Scope: The special theory of relativity is Einstein's most famous achievement and is his other major, revolutionary idea of 1905. We first survey the background, the classical physics that Einstein was overturning. Why did Isaac Newton believe that space and time were "absolute"? How was the idea of absolute space embodied in 19^{th}-century theories of electricity and magnetism—the work of James Clerk Maxwell—which assumed the existence of an electromagnetic "ether," a quasi-material medium in which electromagnetic waves were thought to travel? What was the significance of the famous Michelson-Morley experiment, which failed to detect the Earth's expected motion with respect to the absolute "ether frame"? Why did some critics, such as physicist and philosopher Ernst Mach, have doubts about Newtonian absolute space even before Einstein? And how did the teenage Einstein's own thought experiments make him skeptical of Newton's views?

Outline

I. Einstein's independence as a thinker was especially evident in the case of special relativity. The history and philosophy he read as a student at ETH showed him that the concepts and theories introduced by his predecessors were not set in stone.

- **A.** In 1638, Galileo had pointed out that mechanical phenomena always appear the same with respect to any frame of reference that we would today call an "inertial" frame, a frame moving in a straight line with a constant speed.
  - **1.** Galileo's example of such a frame was a ship sailing on a river. Drop a heavy object from the top of the mast and it falls at the foot of the mast, exactly as it would if the ship were at anchor. A passenger on the ship cannot tell that the ship is moving based solely on mechanical experiments performed on the ship; the ship's motion is detected only relative to observers on the river bank.
  - **2.** Acceleration is another matter. If the ship turns or the wind picks up and gives the ship a push, the passengers feel the difference.
- **B.** The same principle of Galilean relativity is a basic part of Newtonian mechanics, yet Newton famously asserted the existence of absolute space, time, and motion, partly for theological reasons.
  - **1.** Newton thought he had a compelling physical argument for absolute space in his "rotating bucket" thought experiment.
  - **2.** Einstein read about Newton's bucket experiment in Ernst Mach's book on mechanics, in which Mach criticized the experiment and sowed the seeds of doubt about absolute space.
  - **3.** Mach's philosophy, called "positivism," is a radical form of empiricism: the view that all knowledge comes from experience (observation and experiment).
- **C.** It was widely believed in the latter half of the 1800s that absolute space played an important role in Maxwell's physics of electricity and magnetism.
  - **1.** Most physicists of the late 1880s believed that electromagnetic energy and waves lived in a quasi-material medium called the "electromagnetic ether" that continuously filled space, and they reasoned that the frame of reference defined by the electromagnetic ether, the "ether frame," coincided with absolute space.
  - **2.** But if the velocity of light was defined with respect to the ether frame, it seemed obvious that observers on bodies moving through the ether—such as humans on the Earth as it rotates on its axis and revolves around the Sun—should measure a velocity of a ray of light less than c when moving through the ether in the same direction as that ray, and greater than c when moving through the ether in a direction opposite to the ray of light.

II. In 1887, Albert Michelson and Edward Morley, working at the Case Institute of Technology in Cleveland, conducted a famous experiment designed to detect the effect of the Earth's motion through the ether.

- **A.** The Michelson interferometer used mirrors to split a beam of light into two rays moving at right angles to one another. The two rays are then reflected back and recombined.
  - **1.** With the interferometer fixed on the Earth's surface, the two perpendicular rays will move in different directions with respect to the ether, so relative to the interferometer and the Earth's surface, the two perpendicular light rays should travel with different velocities.
  - **2.** If that is so, when the rays recombine, the peaks and troughs of their wave motion will in general no longer be perfectly aligned. The waves will be, as one says, out of phase. But when two light rays that are out of phase are combined and illuminate a screen, they should produce a striking image of concentric circular light and dark bands called an "interference pattern."

B. The Michelson-Morley experiment was a beautifully designed, high-precision experiment—all the more reason why Michelson and the rest of the physics community were shocked when Michelson saw no interference pattern and therefore no evidence that the Earth was moving through the ether.

III. Only after Einstein proposed the special theory of relativity in 1905 did physicists begin slowly to realize that the right way to interpret the result of the Michelson-Morley experiment was as showing that there is no electromagnetic ether, no ether frame, and no absolute space. But the idea of the ether and absolute space was so fundamental to classical physics that physicists struggled to provide other explanations of Michelson's null result.

A. The most ingenious and important of these attempts to save the ether and absolute space was proposed independently by British physicist George Francis FitzGerald and Dutch physicist Hendrik Antoon Lorentz. FitzGerald and Lorentz suggested that bodies moving through the ether could experience a contraction in the direction of their motion, a contraction proportional to their velocity through the ether.

B. If the contraction hypothesis were true, then the Michelson interferometer might contract in the direction of its motion through the ether by an amount that precisely cancels the effect of the different velocities of light. That would explain the null result of the Michelson-Morley experiment.

C. In hindsight, the Lorentz contraction hypothesis looks like a desperate, ad hoc attempt to save a threatened theory, but the idea was not implausible at the time.

D. Moreover, the Lorentz contraction survives, in a transformed way, in Einstein's special theory of relativity. By contrast with Lorentz's theory, the special theory of relativity is a model of elegance, simplicity, and unity. Einstein characterized such aesthetic properties of a theory as *Vollkommenheit*, or "inner perfection."

Suggested Reading:

Bernstein, *Albert Einstein and the Frontiers of Physics*.

Einstein and Infeld, *The Evolution of Physics*.

Galison, *Einstein's Clocks, Poincaré's Maps*.

Kaku, *Einstein's Cosmos*.

Questions to Consider:

1. Think about Galileo's example of the ship for illustrating the mechanical principle of relativity. Would the Earth be an example of the same kind? That is, are there mechanical experiments that we can do on the Earth that reveal to us the Earth's motion?
2. Is it really possible to imagine electromagnetic energy like light or radio waves as existing in empty space and not as inhering in some quasi-material substance like the once-postulated electromagnetic ether?

Lecture Five
Essentials of Special Relativity

Scope: At the heart of Einstein's special theory of relativity is a new way of thinking about place and motion. In relativity theory, a system's location and speed are well-defined only with respect to a specific frame of reference, or state of motion of an observer. As a consequence, the lengths of objects, the intervals of time between two events, and whether or not two events are simultaneous all depend upon the frame of reference within which one asks the question. On the other hand, ironically, the speed of light is unique in being the same in all frames of reference. Stranger still, space and time become entwined with one another in a new structure, a 4-dimensional "space-time." Perhaps most surprising is the fact that this simple change of perspective about motion is what leads to Einstein's signature equation, $E = mc^2$ (energy equals mass times the square of the speed of light), which implies that mass can be converted into energy (and vice versa) and thus holds the secret to the atomic bomb. We take a guided tour of all of these basic principles of special relativity.

Outline

I. Galileo's principle of relativity had been a fundamental part of mechanics for over 200 years. It says that the physical description of any mechanical phenomenon looks the same in all inertial frames of reference.

- **A.** Einstein now asserted that the principle should be universal in its scope, including electrical and magnetic phenomena. Repeated failures to detect physical effects of the Earth's presumed motion through the electromagnetic ether provided an experimental basis for this generalization of the relativity principle.
- **B.** Maxwell's electrodynamics itself suggested another principle, namely, that the speed of light is a constant, independent of the state of motion of the source. Call this the "light principle."
- **C.** These two principles seem to be in conflict with one another. Taken together, they seem to imply that all observers should see light travel with exactly the same velocity, but that violates a fundamental principle of classical Newtonian mechanics, the velocity addition law.

II. Einstein's most important new idea on the road to the special theory of relativity was the realization that the appearance of a paradox rested on the heretofore unquestioned assumption that absolute time defined an absolute criterion of simultaneity for all events.

- **A.** He was right, for if there is absolute time, then there is (as it were) a master clock for the whole universe whose readings determine absolutely and for all observers whether any two events anywhere in the universe are simultaneous.
- **B.** Einstein realized that this was wrong. Whether or not two observers judge two distant events to be simultaneous depends on the observers' states of motion.
- **C.** If there is no absolute distant simultaneity, there is no absolute time, and so the "time" that enters the equations of physics, symbolized by the variable t, has no absolute significance.
- **D.** That means we have to be more careful in writing down rules for translating the description of a physical process in one frame of reference into another frame of reference in a manner that reflects that simultaneity depends on the state of motion of the reference frame.
- **E.** The new transformation rules set down by Einstein are called the Lorentz transformations. They differ from the classical Galilean transformations mainly in the way in which they mix the variables representing space and time and make essential reference to the speed of light.

Galilean Transformations	Lorentz Transformations
$t' = t$	$t' = \dfrac{t - \frac{vx}{c^2}}{\sqrt{1 - \frac{v^2}{c^2}}}$
$x' = x - vt$	$x' = \dfrac{x - vt}{\sqrt{1 - \frac{v^2}{c^2}}}$
$y' = y$	$y' = y$
$z' = z$	$z' = z$

The Galiliean and Lorentz transformations.
It is assumed that the primed frame is moving in the + x direction with velocity v and that c is the speed of light.

III. Among the most surprising consequences of applying the Lorentz transformations are what are known as length contraction and time dilation.

A. Relativistic length contraction takes the same mathematical form as the Lorentz contraction that was introduced to explain away the null result of the Michelson-Morley experiment. But whereas Lorentz contraction was assumed to be a real physical contraction, relativistic length contraction is all a matter of perspective.

B. Time dilation is the corresponding perspectival feature of the behavior of clocks.

IV. The most famous consequence of adopting the new relativistic view of space and time is the equivalence or interconvertibility of mass and energy, expressed in the well-known formula $E = mc^2$.

A. Classical physics had asserted separate conservation laws for energy and mass. Einstein now revealed mass and energy to be two different faces of one still more fundamental aspect of nature.

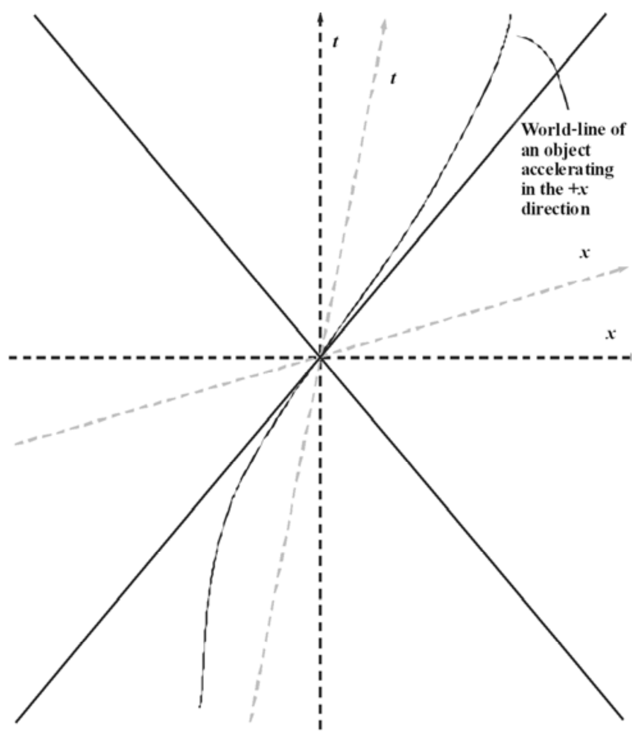
B. Another way in which mass behaves differently in relativity theory is that the mass of a moving object is partly a function of the object's velocity. The faster an object moves, which means the more its so-called kinetic energy grows, the more the object's mass increases. As the object's velocity approaches the speed of light, the mass becomes infinitely large, which is one reason that—according to special relativity—the speed of light represents an upper bound on all physical processes.

Classical Velocity Addition Law	Relativistic Velocity Addition Law
$V = v + u$	$V = \dfrac{v+u}{1+\left(\frac{v}{c}\right)\left(\frac{u}{c}\right)}$

V. In 1908, three years after Einstein published his first paper on special relativity, mathematician Hermann Minkowski (one of Einstein's old teachers) showed that the Lorentz transformations could be viewed geometrically, as just a curious kind of "rotation" in an abstract 4-dimensional "space-time."

A. Minkowski and Einstein both realized that the relativity theory was showing us that what is real is not space and time by themselves, but only the amalgam called space-time.

B. The fundamental elements of space-time were then seen by both Minkowski and Einstein to be not things, but space-time "events," which are just "locations" in 4-dimensional space-time. Physical objects in the traditional sense were now to be represented as "world-lines" in space-time.



Minkowski space-time.
The transformation from the unprimed to the primed reference frame is a rotation that looks in this representation like a squeezing together of the spatial and temporal axes.

Suggested Reading:

Bernstein, *Secrets of the Old One*.

Einstein, *Relativity: The Special and General Theory*.

Einstein and Infeld, *The Evolution of Physics.*

Galison, *Einstein's Clocks, Poincaré's Maps*.

Pais, *"Subtle is the Lord …"*

Stachel, *Einstein's Miraculous Year*, pt. 3.

Questions to Consider:

1. Can it really be the case that there is no objective fact about whether two distant events are or are not simultaneous with one another?

2. Does it really make sense for each of two observers moving relatively to one another to see the other's yardstick as being shorter and the other's clock as ticking more slowly? Why isn't this just a contradiction?

Lecture Six
From Bern to Berlin

Scope: In just nine years, between 1905 and 1914, Einstein went from being an obscure clerk in the Swiss Federal Patent Office in Bern to being the most prominent physicist in Europe, if not the whole world. Only in 1909 did Einstein win his first regular university appointment in Zurich, but after that his rapidly growing reputation brought him a steady stream of enticing offers, with the result that he worked at four different universities in the space of five years. Growing fame and professional success were accompanied by a steady deterioration of his marriage to Mileva, in spite of the birth of their second son, Eduard, in 1910. After Einstein's move to Berlin in 1914, his clandestine affair with his cousin Elsa became public knowledge, leading to a permanent separation from Mileva, who moved back to Zurich with the boys. But Berlin was to become the scene of Einstein's greatest scientific triumph yet, the general theory of relativity.

Outline

I. Einstein's miracle year of 1905 inaugurated great revolutions in physics, but at home in Bern, little changed at first.

- **A.** Einstein still went to work six days a week at the patent office, and he and Mileva cared for their son, Hans Albert.
- **B.** Einstein finally was awarded a doctorate, with a dissertation on a new method for determining molecular dimensions that he did under the supervision of Alfred Kleiner at the University of Zurich. This work was related to the paper Einstein published in 1905 on Brownian motion, which proved very important in convincing physicists of the physical reality of atoms.
- **C.** Eventually the world began to take note of what Einstein had wrought in 1905. He began to correspond with prominent physicists like Max Planck.
- **D.** In 1908 he took the first step up the regular academic ladder when he obtained the habilitation (the second doctorate, as it were) that made it possible for him to offer lectures at the University of Bern.
- **E.** His growing fame was accompanied by growing tensions at home, as the once warm and loving relationship with Mileva began to deteriorate.

II. The papers of 1905 were followed by more, and Einstein's reputation continued to grow, as evidenced by his being invited in 1909 to give a lecture on the theory of radiation at the major annual conference of German-language scientists meeting in Salzburg.

- **A.** That the ever-more famous Einstein had no regular academic position became more and more of a scandal. Finally, in 1909, he was summoned to the University of Zurich as a junior professor of physics.
- **B.** Einstein could hardly be called a scintillating lecturer, but he took his new duties seriously and gathered around him a small group of students. His own work continued apace, and he began to focus on the problem of generalizing relativity.
- **C.** In 1910, the Einstein family grew again with the birth of a second son, Eduard. But the birth of "Tete," as he was known, did nothing to improve the ever-worsening relationship between Albert and Mileva.

III. After his slow start in the profession, Einstein reached the top at a surprisingly young age. In 1911, at the age of just 32, Einstein was offered and accepted a senior, full professorship at the German university in Prague.

- **A.** The move to Prague coincided with Einstein's participation in the first Solvay Congress in Brussels, where he joined a small group of the world's physics elite, including such famous figures as Lorentz, Planck, Henri Poincaré, and Marie Curie.
- **B.** Einstein spent only one year in Prague. Mileva was very unhappy there, far from friends and family, and living conditions were not as comfortable as in Zurich.
- **C.** During the year in Prague, Einstein for the first time came into regular contact with a distinctively Jewish intellectual and cultural world.

IV. Many of the best universities in Europe were now dangling lucrative offers in front of Einstein.

- **A.** The one he chose to accept was from his alma mater, the Polytechnic in Zurich, to which he returned as a senior, full professor in 1912.
- **B.** Offers from elsewhere kept coming, until finally he received an offer that marked a major turning point in his life—an offer from Berlin.

V. It took a lot to persuade Einstein to leave his beloved adopted home in Switzerland, with his close circle of good friends and colleagues in Zurich, to return to the Germany from which he had fled as a teenager.

- **A.** Einstein was offered an appointment as a senior, full professor at the University of Berlin, with no obligations to lecture, along with election to membership in the Prussian Academy of Sciences and the Directorship of a promised new Kaiser Wilhelm Institute for Physics. He moved to Berlin in the spring of 1914.
- **B.** Einstein had another reason for accepting the offer: For some time he had been carrying on a clandestine affair with his cousin Elsa, who lived in Berlin.
  - **1.** When Mileva found out what was really going on, an already strained marriage collapsed. Almost immediately, Mileva moved out of their new apartment in Berlin and set in motion arrangements to move back to Zurich with the two boys. It would be another five awkward years before Albert and Mileva divorced.
  - **2.** Once Mileva had left, Einstein found a new peace. He was free to enjoy Elsa's attentions and to concentrate on his work, with minimal teaching duties.
- **C.** World War I was to break out only a few months after Einstein settled in Berlin, but the Einstein who had already accomplished so much was about to pull off his greatest achievement ever—his completion of the general theory of relativity.

Suggested Reading:

Isaacson, *Einstein: His Life and Universe*, chaps. 7–8.

Levenson, *Einstein in Berlin*.

Stern, *Einstein's German World*.

Questions to Consider:

1. Think about Einstein's growing fame after 1905 and rapid, steady professional advancement after 1909. How might all of this have felt from Mileva's point of view?

2. Do you think that Einstein made the right decision when he accepted the Berlin offer in 1914, or did he wrongly let his love for Elsa and the allure of Berlin overcome his better judgment? Would he have been better off as Lorentz's successor in Leiden?

Lecture Seven
Background to General Relativity

Scope: The special theory of relativity is "special" in that it is restricted to situations in which two frames of reference move with respect to one another with constant speed in a straight line. Soon after introducing special relativity, Einstein asked the obvious question, which is whether it could be extended to include accelerated motions: frames of reference moving with respect to one another with changing speeds and changing directions. Even before introducing the full theory of general relativity in 1915, Einstein discovered through ingenious thought experiments some surprising facts. His "elevator" thought experiment—one imagines a complete physics laboratory falling "freely" in a gravitational field—taught Einstein that, amazingly, a general theory of relativity would be simultaneously a theory of gravitation. His "rotating disk" thought experiment—how does one compute the value of π, the ratio of a circle's circumference to its diameter, on the surface of a spinning disk?—taught him, even more amazingly, that "space-time" in general relativity would be curved.

Outline

I. Shortly after introducing the special theory of relativity in 1905, Einstein began to worry about the fact that its scope was limited to transformations among inertial frames, frames moving relative to one another with constant velocity in a straight line. He asked himself whether a more general theory could be formulated, one valid for transformations among frames moving arbitrarily with respect to one another.

II. Einstein took a first, important step toward a general theory of relativity in 1907 with what we now call the "elevator" thought experiment, through which he discovered a deep connection between accelerated frames of reference and gravitation.

- **A.** Einstein imagined an observer inside a closed space, like an elevator, that is equipped with a complete physics lab. Einstein realized that no experiment performed inside the box could distinguish between the box's being in a strong gravitational field (say, on the surface of the Earth) and its being accelerated rapidly upward (as when an elevator ascends).
- **B.** Einstein concluded that a general theory of relativity, one valid for transformations among mutually accelerated frames of reference, would therefore also have to be a theory of gravity. He formulated this insight in what is known as the "equivalence principle," which asserts that uniform acceleration is equivalent to the presence of a homogenous gravitational field.
- **C.** The equivalence principle cleared up an old puzzle about Newtonian physics, which is why the term for mass in Newton's second law of motion, the force law, always takes the same numerical value as the term for mass in the law of universal gravitation.
- **D.** Newton's second law, or force law, $F = m_b a$, says that force is equal to mass times acceleration. The mass might be that of our ball thrown across the lab. Newton's law of universal gravitation, $F = G\frac{m_b m_e}{r^2}$, asserts that the gravitational force that two bodies exert on one another is proportional to the product of the two masses divided by the square of the distance between them (the constant of proportionality, G, is what we call the "gravitational constant"). Mass in the second law of motion—which is called "inertial mass"—is a measure of a body's inertia, its resistance to changes in its state of motion. Mass in the law of universal gravitation—which is called "gravitational mass"—is a measure of a body's ability to feel and exert gravitational attraction. Why should one and the same property of a body be responsible for both its resistance to changes in motion and its ability to feel and exert gravitational attraction?
- **E.** Einstein's radical answer is that inertial and gravitational mass are equal because they are one and the same property of a body, and that this is a consequence of the equivalence principle's assertion of the indistinguishability of gravitation and uniform acceleration.
- **F.** Another important consequence of the elevator thought experiment is that since electromagnetic phenomena are no more capable of distinguishing acceleration and gravitation than are mechanical phenomena, the paths of light rays should be curved in the presence of a gravitational field. The predicted bending of light in strong gravitational fields like that of the Sun became the basis for the most famous confirmation of the general theory of relativity in 1919.

III. Einstein's next step on the road to general relativity came with another thought experiment, the "rotating disk," which first occurred to him around 1912.

- **A.** Einstein imagined an observer at the center of a flat disk who first measures the ratio of the disk's circumference to its diameter when the disk is stationary, which will of course be π (pi). Now let the disk rotate with a constant radial

velocity and repeat the measurement from the point of view of an observer who remains stationary at the center of the disk. A yardstick applied to and moving with the circumference of the disk will appear to that observer to be contracted, owing to special relativistic length contraction, which means that it will have to be applied more times to get around the whole disk, and so the circumference of the rotating disk will appear to the observer to be greater than the circumference of the stationary disk. But yardsticks applied to measure the diameter will not appear contracted, because the rotational motion of the disk is perpendicular to the diameter. The measured length of the diameter is the same for both the rotating and the nonrotating disk. Putting these various measures together, we get a curious result. When the stationary observer at the center of the disk computes the ratio of circumference to diameter for the rotating disk, the ratio is greater than π.

B. Einstein immediately realized that this meant that the geometry of general relativistic space-time would be radically different from the flat, Euclidean geometry of classical space-time. The space-time of general relativity would be curved.

C. Why this is so may best be understood by imagining first how one does geometry on a surface curved like the surface of a sphere, which we call a "surface of constant positive curvature." A circle on such a surface will be just a circle, but the radius of the circle will be an arc of a great circle—like a part of the equator or a line of longitude. As a result, the ratio of circumference to diameter for a spherical circle will be less than π.

D. The case of Einstein's rotating disk corresponds to another kind of curved surface, a "surface of constant negative curvature," which can be pictured (not perfectly) as sort of a saddle shape. For a circle drawn on such a surface, the ratio of circumference to diameter will be greater than π.

E. There are other equally surprising features of such non-Euclidean geometries of curved surfaces.

   1. The sum of the angles of a triangle on a spherical surface is, in general, greater than the Euclidean value of 180°, whereas on a surface of constant negative curvature the angles of a triangle sum, in general, to less than 180°.

   2. On a spherical surface, with a "straight line" defined as an arc of a great circle, there are no parallel lines, whereas on a saddle surface there are always, for a given straight line, multiple parallels through a point not on the given straight line.

IV. The power of Einstein's thought experiments is demonstrated by the fact that two of the essential ingredients of relativity—the equivalence of acceleration and gravitation, and the curvature of general relativistic space-time—first occurred to Einstein thanks to his "elevator" and "rotating disk" experiments.

Suggested Reading:

Einstein, *Relativity: The Special and General Theory*.

Einstein and Infeld, *The Evolution of Physics*.

Gray, *Ideas of Space*.

Pais, *"Subtle is the Lord …"*

Questions to Consider:

1. The equivalence principle says that one's being uniformly accelerated, as when an astronaut rides a rocket into space, is indistinguishable from one's being in a homogenous gravitational field. But what about uniform deceleration? Does one experience a g-force then? Where would the corresponding gravitating mass be located?

2. Think about what you've learned about the geometry of curved surfaces. If I were a bug constrained to live on and know only about the 2-dimensional surface on which I lived (say, the surface of a leaf), what kind of measurements could I perform to determine the shape of that surface?

Lecture Eight

Essentials of General Relativity

Scope: General relativity is a remarkable scientific theory. We learn how by postulating the curvature of space-time, one explains the free fall of heavy objects near the Earth's surface and a planet's orbital motion around the Sun. Surprising new implications are also examined, as with Einstein's prediction that clocks tick more slowly in stronger gravitational fields. The most famous new prediction of general relativity was that the path of a ray of light would be bent when it passed near a massive object like our Sun, a phenomenon that should be observable when looking at the apparent positions of stars near the edge of the Sun during a total eclipse. Arthur Eddington's confirmation of this prediction in 1919, right after World War I, made Einstein a world-famous figure.

Outline

I. The road from the elevator and rotating disk thought experiments to the final formulation of the general theory of relativity took several years and included a few wrong turns.

- **A.** In 1913, Einstein and his collaborator Grossmann had found the correct generally covariant field equations (equations whose mathematical form remains the same when we translate from one reference frame to another), but they thought that these could not be the correct equations because they wrongly believed that these equations did not give the correct "Newtonian" limit and that the equations failed to yield unique solutions in regions of space-time devoid of matter and energy.
- **B.** As a result, the theory published by Einstein and Grossmann, called the *Entwurf* theory, employs field equations that are not generally covariant.
- **C.** It took Einstein more than two years to sort through his mistakes and correct them. Shortly after Einstein published his final version of the general theory of relativity in November 1915, mathematician David Hilbert published essentially the same gravitational field equations.

II. The main content of Einstein's general theory of relativity is expressed by the field equations, also known as the gravitational field equations or the Einstein field equations:

- **A.** The field equations: $R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = -\frac{8\pi G}{c^4} T_{\mu\nu}$.
- **B.** The way these field equations work is this: The mass-energy at a point in space-time, represented by the stress-energy tensor, $T_{\mu\nu}$, determines (via the field equations) the magnitude of the metric tensor, $g_{\mu\nu}$, at that point of space-time and thus determines the curvature of space-time in that immediate vicinity. The degree of curvature, in turn, determines how both massive bodies and electromagnetic radiation move in that region of space-time.

III. A mental picture helps us to understand how space-time curvature determines motion.

- **A.** Pretend that space is just a 2-dimensional, rubber-like sheet. When there is no massive object resting on the sheet, it is flat. But place a heavy object like a bowling ball on the sheet and it causes the sheet to curve, just as the presence of a massive object like the Sun curves space-time. Now imagine a smaller object, like a marble, rolling across the sheet. If the sheet is flat, the marble rolls in a straight line. But if the sheet is curved, then the marble follows a "curved" path. If the marble is moving fast enough and is far enough away, it might only be deflected a bit by the bowling-ball-induced curvature, much like Voyager 1's trajectory was deflected during its flyby of Jupiter in 1977. But if the marble is moving more slowly or is closer to the bowling ball, then it might be "captured" by the bowling-ball-induced curvature and revolve around the bowling ball, just as a planet revolves around the Sun. Precisely the same kind of behavior would occur with rays of light following "curved" trajectories in the vicinity of massive bodies.
- **B.** We speak, in this way, of a massive body or a ray of light following a "curved" trajectory in space-time. But if we were being more careful, we would say that in the absence of nongravitational forces, light and material bodies follow "geodesic" trajectories, which are the lines of shortest distance in a curved space-time. It is space-time itself that is curved, not the trajectories of light and material bodies moving in an unforced way in space-time.

IV. The general theory of relativity has some truly striking implications.

- **A.** First, general relativity precisely accounts for a famous problem in the classical Newtonian description of planetary motion, a problem called the "anomalous precession of the perihelion of Mercury," which is a slightly faster than predicted rotation of the long axis of the planet's orbit.
- **B.** A second implication was a previously completely unknown effect called the "gravitational red shift." Einstein showed that the rate at which any periodic process proceeds—like the motion of a light wave—will be affected by

the presence of a gravitational field. The stronger the gravitational field, the more the periodic process is slowed down. With light waves and other forms of electromagnetic radiation, this means that the frequency will be lower in a stronger gravitational field. In the case of visible light, lowering the frequency means shifting the color toward the red end of the spectrum, hence the name of the phenomenon, the gravitational red shift. The rate at which a clock ticks will also be slowed when the clock is in the presence of a gravitational field. (This general relativistic slowing of clock rates differs from the special relativistic phenomenon of time dilation.)

- **C.** The most famous prediction of general relativity was the bending of light near massive objects like the Sun. Einstein realized that this prediction could be tested during a total eclipse, when the Sun's light is blocked by the Moon. In 1919, British astronomer Arthur Eddington organized expeditions to Africa and South America to test Einstein's prediction. Eddington's announcement in November 1919 that they had confirmed the prediction catapulted Einstein from being merely the world's most highly respected physicist to being, perhaps, the world's most famous person.

V. Earlier, German astronomer Erwin Freundlich had led an expedition to the Crimean region of Russia to test Einstein's light-bending prediction during a total eclipse in August 1914.

- **A.** World War I broke out before the eclipse, and Freundlich and his colleagues were seized by the Russians and held as enemy aliens.
- **B.** This turned out to be a lucky break for Einstein, because Einstein's early *Entwurf* version of general relativity gave the wrong prediction for the gravitational bending of light near the Sun.

VI. Einstein, a German Jewish pacifist, and Eddington, a Quaker pacifist, seized upon the opportunity of Eddington's confirming Einstein's prediction of the bending of light near the Sun in 1919 to prove that science could transcend politics and that the common pursuit of scientific truth could help to reunite a war-torn Europe.

Suggested Reading:

Einstein, *Relativity: The Special and General Theory*.

Einstein and Infeld, *The Evolution of Physics*.

Geroch, *General Relativity from A to B*.

Pais, *"Subtle is the Lord …"*

Renn, *The Genesis of General Relativity*.

Wald, *Space, Time, and Gravity*.

Questions to Consider:

1. Think about the bowling ball on the rubber sheet as being like the Sun's inducing curvature in space. If the Sun were to disappear instantaneously, would its gravitational effects instantly disappear at arbitrary distances, or would it take time for those gravitational effects to disappear?
2. Clocks tick more slowly in stronger gravitational fields. Imagine that you're falling into a gravity well, where the force of gravity grows infinitely strong at the center. Measured by your own wristwatch, how long would it take you to reach the center? (Assume, for the sake of the argument, that you and your watch would not be destroyed by the strong gravitational forces.)

Lecture Nine

From Berlin to Princeton

Scope: Einstein worked in Berlin for nearly 20 years, from 1914 to 1933. He arrived in triumph, already the most famous German physicist, but he left as a refugee, his fame no protection from Hitler's insane assault upon German science and learning in the name of Aryan racial supremacy. Divorce from Mileva and marriage to Elsa brought about major changes in Einstein's personal life. Confirmation of the general theory of relativity in 1919 made him world famous. He received the Nobel Prize in 1922. Travel took him all over Europe and to the United States, Japan, Palestine, and Argentina. Regular visits to Caltech in the early 1930s were the prelude to Einstein's permanent move to Princeton late in 1933.

Outline

I. Einstein's first four years in Berlin were dominated by war. His income and Elsa's family wealth shielded them from the worst, but the stress of wartime life and a poor diet put Einstein's own health at risk. When the war ended suddenly on November 9, 1918, and the Kaiser abdicated, there was an outbreak of revolutionary turmoil and, later, a near total collapse of the economy.

- **A.** Einstein could not avoid being drawn into the maelstrom. For example, when student radicals arrested the rector of the University of Berlin, it fell to Einstein to lead a delegation to win the rector's release.
- **B.** A measure of political stability was achieved with the establishment of the new Weimar Republic in February 1919, but postwar economic recovery was long in coming. Even senior academics found themselves facing privation.
- **C.** An unhappy consequence of postwar tensions in Germany was that Jews became a scapegoat for Germany's losing the war; the anti-Semitism reached all the way into the sciences.

II. In the midst of this turmoil, Einstein's personal life began to stabilize.

- **A.** Albert and Mileva finally divorced in 1919, and Albert married Elsa shortly thereafter.
- **B.** Elsa relished her role as wife of a world-famous scientist and created for Einstein a comfortable upper-middle-class home that contrasted starkly with the bohemian world of his university days.
- **C.** Not all was domestic bliss, however. More than a few women were drawn to Einstein, and he indulged in a number of not-so-secret extramarital affairs. Elsa, the realist, made her peace with Einstein's philandering, perhaps seeing this as the price of marriage to a famous man.

III. Einstein had become truly world famous; Eddington's 1919 confirmation of general relativity made Einstein front-page news in every major newspaper around the world.

- **A.** The Nobel Prize in Physics followed in 1922 (it was the 1921 prize, delayed by a year). Surprisingly it was awarded not for relativity but for the photoelectric effect.
- **B.** Invitations to lecture poured in. His first trip to the United States was in 1921, the purpose being to raise funds for the planned Hebrew University of Jerusalem. In the spring of 1922, he was the first prominent German scientist to make an official visit to France since the end of World War I. In late 1922 and early 1923, Albert and Elsa went on a grand tour that took them all the way to Japan. On the way home they visited Palestine. In 1925 it was South America. Vienna and London got to know Einstein as well, and he regularly visited in Leiden, where he held a part-time appointment.
- **C.** On the occasion of Einstein's 50^{th} birthday, in 1929, his home town of Berlin sought to honor him with the gift of a summer house on one of the many lakes on the city's outskirts so that he could more easily pursue his love of sailing. These plans fell through but did lead to Einstein's having built for himself his own much-beloved summer house in the Berlin suburb of Caputh, near Potsdam.

IV. The late 1920s and early 1930s, after Germany's economy stabilized and before Hitler rose to power, were perhaps the happiest years of Einstein's life.

- **A.** Berlin in those years rivaled Paris as an energetic, sophisticated, cosmopolitan city. It was also the center of a vibrant Jewish community.
- **B.** Berlin was a magnet for bright young physics students, like Eugene Wigner and Leo Szilard. Niels Bohr, Max Born, Wolfgang Pauli, and Werner Heisenberg all stopped in Berlin at one point or another.

C. Einstein's student Hans Reichenbach was to become famous in Germany (and later the United States) as one of the leaders of the movement in philosophy of science known as "logical positivism," "logical empiricism," or "scientific philosophy." Einstein and Planck arranged for Reichenbach to be given a new chair in the philosophy of science in the physics department at the University of Berlin.

V. In the late 1920s, Germany was still the world's leading scientific nation, but American universities were working hard to achieve parity.

- **A.** Perhaps the most ambitious was the comparatively young California Institute of Technology, in Pasadena, which recruited Einstein to a regular visiting appointment starting in 1931.
- **B.** With minimal duties, Einstein got to meet America's scientific elite and its Hollywood elite as well.
- **C.** Einstein was just ending his third visit to Caltech in the late winter of 1933 when Hitler became Germany's new chancellor. Under no illusions about Hitler's intentions, Einstein made up his mind immediately that he would never return to Germany. Albert and Elsa sailed back to Europe, and they found a temporary safe haven in Belgium under the protection of the Belgian royal family, with whom Einstein had become friends few years earlier.

VI. Einstein received offers from London, Paris, Madrid, and Jerusalem, but he and Elsa chose Princeton.

- **A.** Many months earlier, Einstein had begun negotiating with Abraham Flexner about a part-time appointment at the new Institute for Advanced Study that Flexner had founded in Princeton. That part-time position became a full-time one, and Einstein arrived in his new American home in October 1933.
- **B.** Leaving Europe as a refugee from Nazism was not an easy task. He left behind two sons, two stepdaughters, his first wife, many relatives, and many friends. He left behind the academic world in which his mind had been shaped and tested, the cultural world in which his love of music and literature had been nurtured, and the social and political world in which his conscience had been formed.
- **C.** Einstein was surprised to see how few of his former colleagues had the courage to oppose the Nazi assault on science and learning.
- **D.** Einstein's summer house at Caputh was raided and seized by the Nazis. They also raided his Berlin apartment, but not before Einstein's son-in-law, Rudolf Kayser (husband of Elsa's daughter Ilse), managed to get nearly all of his papers safely away. Eventually Einstein's papers and even the furniture from the Berlin apartment made it safely to Princeton with the help of the French diplomatic service.
- **E.** It was surely with a great sigh of relief that Albert and Elsa settled into the small, quiet university town of Princeton. The contrast with the fast-paced life of a world city like Berlin could not have been greater. But 112 Mercer Street, Princeton, New Jersey, would be Einstein's address for the last 20 years of his life.

Suggested Reading:

Isaacson, *Einstein: His Life and Universe*, chaps. 10, 12–14, 16, 18.

Levenson, *Einstein in Berlin*.

Stern, *Einstein's German World*.

Questions to Consider:

1. Why, in your opinion, did it take the United States so long to achieve parity with Germany in the advanced training of science students?
2. Does it make an important difference in the way science is done if one works in an exciting world city like Berlin as opposed to a quiet university town like Göttingen?

Lecture Ten
Philosophical Challenge of the New Physics

Scope: Quantum theory and relativity theory both presented deep challenges to old philosophical views of the universe. Quantum theory is nondeterministic, postulating an essential randomness in elementary quantum events, and so threatens the long-established idea that, as Einstein once famously said, "God does not play dice with the universe." Relativity theory contradicts the claim—famously defended by Immanuel Kant—that absolute, Newtonian space and time are necessities of thought. One is not surprised that Einstein's new physics provoked a philosophical reaction and stimulated a philosophical revolution, the most important aspect of which was the rise of the point of view known as "logical positivism," the most influential school of thought in 20th-century philosophy of science. Logical positivism famously insists that the only meaningful concepts and theories are those whose experimental and observational roots can be made crystal clear. It follows that ethics and politics lack "cognitive meaning" and must be seen as no more than expressions of emotional attitudes. Whether and how one can reason from special relativity to the meaninglessness of ethics are obviously controversial questions.

Outline

I. The dominant philosophical figure at the end of the 19th century and the beginning of the 20th century was the late 18th-century German philosopher Immanuel Kant.

- **A.** Kant was deeply impressed by Newtonian mechanics as the very epitome of scientific knowledge, and he took as his philosophical project the attempt to understand what it is about the nature of human knowledge that made Newton's great achievement possible.
- **B.** Kant reacted against two earlier philosophical traditions. One was the German rationalist tradition in metaphysics, represented by Leibniz. The other was the British empiricist tradition in epistemology (the theory of knowledge), represented by Hume.
- **C.** Kant's new approach, called the "transcendental turn," sought the necessary features of scientific knowledge by asking how knowledge must be organized in order for scientific cognition to be possible. The "synthetic, a priori" principles of organization were viewed by Kant as being imposed upon our knowledge of nature, or structuring our knowledge of nature, as the knower's contribution to knowledge. They are synthetic in the sense that they are not just the result of analyzing concepts, and they are a priori in the sense of being logically prior to all experience.
- **D.** Foremost among these necessary, a priori features that structure human knowledge are space, time, and causality. Space and time for Kant are the absolute space and time of Newton, with space being the space truly described by Euclidean geometry.
- **E.** But there one sees the problem: The quantum theory that Einstein helped to discover denies strict determinism and so denies the a priori nature of causality, and the relativity theory denies that space is Euclidean and that space and time are absolute.

II. There had been other challenges to Kant, but the challenges from quantum theory and relativity theory were the most severe, because they pretended to come with the same kind of empirical warrant that earlier set Newton's physics apart from the medieval natural philosophy it had helped to overthrow.

- **A.** There were ingenious attempts to salvage some or all of Kant's doctrines. For example, some defenders of Kant argued that his claims about space and time were to be interpreted as pertaining to psychological space and time (the way the mind apprehends space and time), not to physical space and time.
- **B.** The most sensible defense was to argue that Kant had been too specific in his claims. For example, some of Kant's defenders, like Ernst Cassirer, suggested that while Kant was wrong to claim that space had a specifically Euclidean (or flat) geometrical form, there were nevertheless weaker, "topological" facts about space that were still necessary a priori features of our science.
- **C.** There was one other way to defend Kant, by simply denying the truth of relativity. This was not an option seriously entertained by Einstein or other philosophers impressed by what he had achieved.

III. The French physicist, mathematician, and philosopher Henri Poincaré proposed a different way of saving even Kant's claim that the geometry of physical space is Euclidean.

- **A.** The sum of the angles of a triangle on a non-Euclidean surface differs from the Euclidean value of 180°; the size of the difference depends on the area of the triangle. The larger the triangle, the greater the difference, and the difference shrinks to the Euclidean value as the triangle becomes infinitely small.

B. Imagine that one measures via telescopic observations the angles of a triangle formed by a distant star and two locations six months apart on the Earth's orbit. Assume that the observed angles sum to more than 180°. Does that prove, empirically, that the geometry of space is non-Euclidean?

C. No, said Poincaré: The angle measurements made an unspoken assumption that light rays follow straight-line paths. But this assumption has the status of a convention that we may choose to accept or change. Instead of assuming that light follows straight-line paths, we might choose to assume that light follows curved paths, which would allow us to assert that space itself still has a flat, Euclidean geometry.

D. Poincaré argued that one should choose the convention that produces the simplest geometry, and since Euclidean geometry is simpler than its rivals, a reasonable person would always adopt the convention that light rays followed curved paths in a fundamentally flat space.

IV. Historically, the most important philosophical reaction to Einstein's new physics was the movement known as "logical positivism" (also "logical empiricism," or the "Vienna Circle"), the most prominent members of which—Moritz Schlick, Rudolf Carnap, Hans Reichenbach, and Philipp Frank—all started their careers as physicists or with a technically sophisticated engagement with the philosophical implications of relativity theory.

A. Einstein knew most of these philosophers of science well and counted some among his friends.

B. Starting in the mid-1910s and early 1920s, logical empiricists sought a philosophical understanding of modern physics that respected both the old empiricist principle that experiment and observation are the ultimate arbiters of truth for scientific theories and the Kantian and conventionalist insight that the knower contributes something to cognition. They wanted to show why one should think that there are compelling empirical reasons for accepting the relativity theory's radical claims about the non-Euclidean character of space-time.

C. The foundation of the logical positivist philosophy of science is the "verifiability criterion of meaningfulness," also known as the "verificationist" principle. It asserts that the only meaningful statements are those that are logically true or false (sometimes called "analytic" statements) or those that are demonstrably true or false on the basis of experience alone (sometimes called "synthetic" statements). The logical empiricists held that the meaning of empirical statements was nothing more than the experience that confirms or disconfirms them.

D. They granted Poincaré's point about the conventional choice of light ray paths so that, in a trivial sense, one could save Euclidean geometry by choosing a different convention. But they argued that since two such alternative theories were based on the same observations, and since the only meaning is empirical meaning, the difference between two such theories was no more significant than the difference between two languages or two systems of measurement units. The same empirical truth was expressed in two different ways.

E. They disagreed with Poincaré about how to apply the criterion of simplicity in choosing between empirically equivalent theories. The logical positivists said that simplicity was a question not just about geometry alone but about geometry and physics taken together. Judging in that way, they argued, relativity theory, even with its implications about the non-Euclidean character of space-time, was the hands-down winner.

F. By the mid-1920s, Einstein had concluded that his friends Schlick, Reichenbach, and Carnap were going too far down the wrong path, both because their radical empiricism made them skeptical of metaphysics and because they held that since ethical judgments are not verifiable, such claims lack meaning.

Suggested Reading:

Einstein, "Geometry and Experience."

Einstein and Infeld, *The Evolution of Physics*.

Fine, "Einstein's Realism."

Howard, "Albert Einstein as a Philosopher of Science."

Questions to Consider:

1. Relativity and quantum mechanics challenge Kant's claim that space, time, and causality are a priori features of scientific knowledge. In your opinion, should science be based on some necessarily true, self-evident first principles or should everything be up for grabs in science?
2. Were the logical empiricists right to assert that science, on the one hand, and morals and politics, on the other hand, represent two fundamentally different orientations to the world? Were they right to assert that morals and politics don't constitute knowledge but are just ways of expressing emotional attitudes?

Lecture Eleven
Einstein's Philosophy of Science

Scope: Einstein triggered the development of logical positivism and was on friendly terms with many of its major figures, but he strongly dissented from central pieces of logical positivist doctrine. We examine Einstein's rather different way of understanding how scientific theories are related to the reality physics aims to describe and to the experiments and observations upon which theory is based. We will try to understand how, for Einstein, observation and experiment can be the final arbiters of scientific truth even though, as Einstein said, scientific theories are the "free creations of the human mind." Crucial to Einstein's philosophy of science is a "holistic" view of theories and human knowledge more generally, the idea being that one never tests individual scientific claims in isolation—not even the predicted bending of light near the Sun—but only whole theories or sets of theories. Among other interesting consequences of Einstein's "theory holism" is his being able to reconcile deep respect for ultimate authority of experimental evidence with his equally famous appreciation of aesthetic properties like simplicity and beauty as guides in the search for scientific truth.

Outline

I. Many people are surprised to learn how much time and effort Einstein devoted to the philosophy of science. From early on, Einstein stressed the crucial role of philosophy in physics, arguing that philosophy gives the physicist the independence of judgment needed to make revolutionary innovations.

- **A.** Einstein was personally acquainted with most of the major thinkers in the logical positivist movement and initially made common cause with them, but by the mid- to late 1920s, Einstein parted company with the positivists.
- **B.** He was especially concerned by the positivists' elevation of the "verifiability criterion of meaningfulness" to the status of dogma.
- **C.** Einstein's reasoning was more subtle. If he had demanded direct observational evidence to validate every scientific concept and claim, how, for example, could he have argued in 1905 that Brownian motion proved the existence of atoms and molecules? At the time we had no direct observational evidence for atoms and molecules, but their existence could be *inferred* from indirect evidence.

II. Einstein took up the question of how we understand the difference between direct and indirect evidence in his lectures on electrodynamics in 1910 to 1911.

- **A.** When we do science, Einstein said, we do not test every assertion by itself. Instead, we test theories in their entirety—and if a whole theory passes the test, it's reasonable, at least provisionally, to assume that each of the theory's individual claims inherits some of that empirical confirmation.
- **B.** This way of thinking had been strongly reinforced a year or so earlier when Einstein read the very influential book *La Théorie physique, son objet et sa structure* (*The Aim and Structure of Physical Theory*), published in 1906 by the French physical chemist, historian of science, and philosopher of science Pierre Duhem.
- **C.** The two theses most commonly associated with Duhem's philosophy of science, both of which Einstein endorsed, are "epistemological holism" and "underdeterminationism."
  1. "Holism" is the thesis that it is always only whole bodies of theory we test in science, never a single proposition standing alone.
  2. "Underdeterminationism" is the thesis that theory choice in science is always "underdetermined" by empirical evidence.

III. One consequence of the logical empiricists' stringent application of the verifiability criterion of meaningfulness is skepticism about the role of "unobservables" in science, such as Boltzmann's atoms or Maxwell's electromagnetic ether.

- **A.** Logical empiricists often counseled not using such concepts at all, or treating them as conceptual shorthand. In this view, later called "Instrumentalism," scientific theories were nothing more than convenient descriptions of observable phenomena or tools for organizing experience and making predictions.
- **B.** An alternative view, now called "Scientific Realism," is more accepting of indirect evidence and asserts that science aims to give us true representations of even unobservable physical reality.
- **C.** Einstein's philosophy of science was more subtle than either of these two alternatives. He believed that science aimed for a description of physical reality, and he trusted simplicity to help in sorting through alternative theoretical accounts of that reality, but he knew that there could always be more than one well-confirmed theory in any scientific domain.

IV. Einstein worried that if theory were tied too closely to experience, nothing would be left for the theorist.

A. In Einstein's day, theoretical physics was a brand-new field. One way to devalue theory is to argue that theory is nothing more than a shorthand description of experience. But the theoretical physics that Einstein prized was distinguished by theories that are "free creations" of the scientific intellect.

B. Einstein made a distinction between "principle theories" and "constructive theories."

1. A principle theory consists of a set of principles, each of which is distinguished by rock-solid empirical credentials, such as the light principle and the relativity principle in the special theory of relativity.

2. A constructive theory is a theory that pretends to construct a model or picture of deep physical reality, such as the Bohr model of the atom.

3. Einstein held that the role of principle theories is to guide the search for deeper constructive theories.

V. Especially after the successful outcome of his search for a general theory of relativity in 1915, Einstein was convinced of the power of mathematical simplicity as a guide to truth in physics.

A. He saw that many of the errors he made along the way were the result of his not trusting his instincts in accepting the simplest set of gravitational field equations—which he had discovered as early as 1912, only to reject them and then return to them in the end.

B. Einstein regarded his unfortunate addition of the cosmological constant to his field equations in 1917 to block expanding universe solutions as a "blemish" on the beauty of the theory, and he was glad to remove it in the early 1930s after Edwin Hubble's observations of distant galaxies proved that our universe is expanding.

C. But for all of his faith in simplicity, Einstein admitted that in spite of long effort, he could not define exactly what simplicity meant.

D. Duhem's holism also gave Einstein his own distinctive answer to Kantian a priorism. In the spirit of Duhem, he noted that there is no reason, in principle, why just some specific elements of theory, like the claim about Euclidean geometry, had to be held fixed. We seek the simplest theory of nature, and if that simplest theory posits curved space-time, then so be it.

Suggested Reading:

Einstein, "On the Method of Theoretical Physics."

Einstein, "Physics and Reality."

Holton, "Mach, Einstein, and the Search for Reality."

Howard, "Albert Einstein as a Philosopher of Science."

Questions to Consider:

1. Do you think that it's reasonable for science to pretend to give true descriptions of unobservable reality (the "scientific realist" position) even in areas in which, in principle, the structure and properties of systems (like quarks, perhaps) can only be *inferred* and never directly detected?

2. Einstein said that scientific theories are the "free creations" of the human intellect. In what sense are these creations "free"? Is it like the freedom of the poet? What exactly is the role of imagination in science?

Lecture Twelve

Zionism, Pacifism, and Internationalism

Scope: The first stirring of Einstein's social conscience was evident when, as a teenager, he voluntarily renounced his German citizenship because of his dislike of German militarism and then eagerly pursued citizenship in a Switzerland proud of its tradition of neutrality. As Einstein's growing physics reputation drew him onto a larger public stage, his social and political involvements expanded as well, encompassing a lonely protest against German war aims during World War I, an embrace of the Zionist cause in the early 1920s, and strident advocacy of pacifism throughout the 1920s. Einstein became a symbol and a target. Starting in the early 1920s, his physics was vilified by early friends of fascism as the epitome of "Jewish physics," and threats to Einstein's life even forced him to leave Germany for a while. Fortunate to be in the United States when Hitler took power in 1933, Einstein never returned to Germany, declaring that he would not live in a country in which basic democratic rights and liberties were not respected. The once famous pacifist was so appalled by Hitler that he urged resistance from a very early date.

Outline

I. Einstein's social conscience was awakened early. He voluntarily renounced his German citizenship at the age of 16. His liberal political tendencies were no doubt reinforced during his student life in the bohemian cultural environment of Zurich, long a home to political refugees and avant-garde culture.

- **A.** It was only after Einstein's move to Berlin and the outbreak of World War I in 1914 that Einstein began to express himself publicly. Einstein was appalled to find himself back in a Germany at war and was dismayed to see colleagues like Planck supporting German war aims.
- **B.** Late in 1915, he took the somewhat risky step of cosigning a manifesto opposing German rationalizations of the war. He also joined the New Fatherland League, an organization espousing the cause of internationalism, and he used his Swiss connections to make contact with other pacifists.

II. The German collapse in November 1918 unleashed radical political upheaval in Germany. At the same time, right-wing Germans seeking an excuse for Germany's defeat turned their attention to Germany's Jews, sowing the seeds of the virulent postwar anti-Semitism that would bear such bitter fruit a few years later. One expression of this was the "German physics" movement, which vilified Einstein and relativity as epitomizing the worst tendencies of what was termed "Jewish physics."

- **A.** After the 1922 assassination of Walther Rathenau, a Jewish industrialist and foreign minister of Germany's new Weimar Republic, the situation grew so grim that Einstein was forced to retreat from public view for a while.
- **B.** But after Eddington's eclipse expedition yielded confirmation of general relativity in the fall of 1919, there was little that Einstein could do to stay out of the public eye.

III. The leaders of the Zionist movement saw an opportunity. Einstein had never been a devout Jew, but finding himself part of a vibrant, progressive Jewish cultural world in a Berlin being flooded with orthodox Jewish refugees from the East and seething with anti-Semitic agitation, Einstein realized that he could use his fame to help promote the cause of constructing a safe haven for displaced Jews in Palestine.

- **A.** Einstein agreed to accompany Chaim Weizmann in 1921 on a fundraising tour of the United States for the new Hebrew University of Jerusalem. For the rest of his life, Einstein lent his support to the Zionist movement. But he was always careful to explain that he supported "cultural Zionism," not "national Zionism." That meant support for Jewish refugees in Palestine and for institutions like Hebrew University, but not support for a Jewish national state, which he feared would lead to conflict with Palestinian Arabs.
- **B.** When Weizmann, by then the president of Israel, died in 1952, the presidency was offered to Einstein, but he declined.
- **C.** At the time of Einstein's death in April 1955, the very last document on which he was working was yet another plea for understanding between Jews and Arabs.

IV. Another cause that Einstein realized his fame would serve was pacifism. By the late 1920s he had become the pacifist movement's most prominent public voice.

- **A.** Einstein's sympathy for pacifism was strong and sincere, but when Hitler became chancellor of Germany in 1933, Einstein realized (far earlier than did many world leaders) that only a strong military response would protect the world from Hitler's madness.

- **B.** Many of Einstein's pacifist allies were deeply disappointed, but Einstein explained that under the circumstances prevailing after Hitler's ascension to power, the larger causes of peace and security were now best served by arming for defense.
- **C.** Einstein did not think of himself as abandoning his pacifist principles. He had little faith in the capacity or willingness of German citizens to restrain Hitler, and he feared the threat to the world if Hitler were to get the atomic bomb before the Allies had a credible deterrent.
- **D.** Einstein did not make the same argument after World War II when the threat from Hitler's Germany was replaced by the threat from Stalin's Soviet Union. He was under no illusions about life under Stalin, but in the very different circumstances of the Cold War, he thought the cause of peace was better served by diplomacy than by aggressive military posturing.

V. Einstein knew that world peace required the establishment of new institutions transcending the local concerns of individual nations. He was saddened by how quickly the ideal of an international community of science was abandoned after the outbreak of World War I, and he used his influence to rebuild that community after the war ended.

- **A.** Einstein was the first prominent German scientist to make a highly publicized, official visit to France after the war (in 1922).
- **B.** Also in 1922, Einstein joined the new Committee of Intellectual Cooperation associated with the League of Nations. This organization sponsored scholarly conferences and initiatives like the Einstein-Freud correspondence, *Why War?*, in 1933.
- **C.** Einstein had been reluctant to join an organization dominated by the French, and less than a year after joining he resigned from the committee as a gesture of protest after France and Belgium occupied the Ruhr district of Germany (though he later rejoined the committee).
- **D.** This would not be the last time the League of Nations proved itself incapable of preventing member nations from violating the League's own rules, nor would it be the last time Einstein expressed his disappointment with the League's failures.

VI. Disappointments such as these led Einstein, finally, to conclude that the only effective way to overcome the dangers of excessive nationalism was through a world government commanding sufficient military strength of its own so as to be able to enforce international law.

- **A.** Einstein understood that effective world government implied the renunciation of individual national sovereignty. This was consonant with his own longstanding aversion to nationalism and his sense of himself as not being attached to any particular state or nation.
- **B.** Einstein's insistence that a transnational authority have sufficient police and military power to enforce its laws and rulings implied limits to his pacifism, even before he surprised his pacifist allies by urging forceful resistance to Hitler.
- **C.** During the 1930s and 1940s, Einstein's advocacy of world government was more muted, but as soon as World War II ended he resumed the argument for an end to national sovereignty in favor of a world organization with far more authority and power than was contemplated by planners of the new United Nations.
- **D.** Einstein's postwar advocacy of world government found its clearest expression in his promotion of a new book, *The Anatomy of Peace*, by Emery Reves.

Suggested Reading:

Nathan and Norden, *Einstein on Peace*.

Rosenkranz, "Albert Einstein and the German Zionist Movement."

Rowe and Schulmann, *Einstein on Politics*.

Questions to Consider:

1. Was Einstein right to put his scientific fame to use in promoting the many social and political causes about which he cared, or is the scientist's place rightly confined to the classroom and the laboratory?
2. When Einstein urged armed resistance to Hitler and the building of an atomic bomb, was he guilty of inconsistency with respect to his fundamental pacifist commitments?

Lecture Thirteen

Einstein the Inventor and Musician

Scope: Einstein was not just a theoretical physicist. He had other passions in life, two of them being invention and music. He grew up in a technical environment populated by electrical engineers, and throughout his life he took pleasure in thinking about devices from airfoils to refrigerators. He consulted with industry about gyrocompasses and with the U.S. Navy about torpedoes. Listening to music and playing it on his violin were passions as well. But music and invention were not just hobbies or recreation for Einstein. There is something of the inventor and the musician also in Einstein the theoretical physicist.

Outline

I. Invention and music were significant parts of Einstein's life from an early age.

A. Einstein grew up among machines and engineers. The firm run by his father and uncle made electrical power generating and distribution systems, and for part of the family's time in Munich their home was on the grounds of the factory. The young Einstein was at home in the machine shop and the drafting studio.

B. Einstein also grew up with music, and he mastered the violin at an early age. His mother, Pauline, encouraged his study and made music an important part of the household.

II. At the Polytechnic, Einstein was famous for disregarding instructions and doing things his own way, sometimes with literally explosive consequences. But he *wanted* to do the experiments his own way; however lacking in skill he might have been, he loved to tinker. Examples of his inventiveness abound.

A. While still working at the patent office in Bern, Einstein joined with Conrad Habicht (his Olympia Academy friend) and Conrad's brother Paul in the design and construction of a device they called the *Maschinschen* (the "little machine") for the amplification and measurement of small electrical potentials.

B. During World War I Einstein had an idea for a new airfoil design that he shared with the German military. It was an odd shape, with a kind of hump in the middle of the wing. A prototype of the Einstein wing was actually tested but nearly killed the pilot.

C. From a financial point of view, Einstein's most successful venture into the realm of invention grew out of his work at the patent office, when in 1914 the German firm of Anschütz-Kaempfe, remembering his earlier patent work, recruited Einstein as an expert witness in a patent-infringement suit over the design of the gyrocompass.

D. In 1927, Einstein and Leo Szilard applied for a joint patent for an innovative refrigerator design with no moving parts. It used a process employing pressure changes to drive the refrigeration cycle, with butane as the refrigerant.

E. Einstein and his friend Gustav Bucky were awarded a patent in 1936 for the design of a "light intensity self-adjusting camera," which used a photoelectric cell to gauge the intensity of incoming light and then move a celluloid screen of variable transparency behind the aperture.

F. The same engineer's mentality that Einstein brought to his work as an inventor also helped him in his collaborations with experimentalists such as Freundlich, Wander Johannes de Haas, and Walter Bothe.

G. More than mental recreation, Einstein's tinkering can be seen in his eight-year quest for a general theory of relativity or his decades-long struggle to understand the riddle of the quantum world.

III. Just as the mind of the engineer was involved in Einstein's physics, so was the mind of the musician.

A. Einstein could play the piano, but his favorite instrument was the violin. He was not good enough to have had a concert career, but he was good enough to impress many people, and he loved playing music with friends.

B. Mozart was his favorite composer, but he also liked Bach and Beethoven. Intimate chamber music of the kind he could play himself was what he enjoyed most. Duets for piano and violin filled the home of Einstein's closest physicist friend, Paul Ehrenfest, in Leiden.

C. Music opened many doors for Einstein. Playing music together is what cemented the friendship between Einstein and the Queen of Belgium. Music also led to his friendship with African American soprano Marian Anderson.

IV. Music provided Einstein with images and metaphors. Einstein said of Bohr's work, "This is the highest form of musicality in the realm of thought."

A. Like the ancient Pythagoreans, Einstein was tempted to think that an essentially musical or aesthetic notion of harmony or simplicity was the surest guide to truth in recondite realms of fundamental physics.

B. There was a spiritual dimension to Einstein's appreciation of music. Arthur Schopenhauer, one of Einstein's favorite philosophers and an important influence on his idea of "cosmic religion," held that musical experience can carry us beyond the veil of Maya to ultimate reality, where the deepest unity can be found.

C. In a 1929 interview, Einstein said, "If I were not a physicist, I would probably be a musician. I often think in music. I live my daydreams in music. I see my life in terms of music. … I get most joy in life out of my violin."

Suggested Reading:

Graff, "The Automatic 'Concrete People's Refrigerator.'"

Hughes, "Einstein the Inventor."

Wolff, "Albert Einstein and Music."

Questions to Consider:

1. Einstein the theoretical physicist and Einstein the inventor used the same brain. But many people assume that science and inventing differ in that one theory is always closest to the truth whereas there's often more than one good technical solution to a technical problem. Does Einstein's example suggest that this common view is wrong, or did Einstein prize invention as providing relief from the more stringent demands of scientific discovery?
2. Einstein the physicist and Einstein the musician also used the same brain. But many people assume that scientific rigor and aesthetic taste are two very different aptitudes. Does Einstein's example suggest that this common view is wrong, or was music, for Einstein, just a form of recreation, a vacation from his physics day job?

Lecture Fourteen

On the Road to the New Quantum Mechanics

Scope: Einstein made many contributions to the development of the quantum theory between 1905 and 1927, when quantum mechanics was finally given its modern, mathematical formulation in Werner Heisenberg's matrix mechanics and Erwin Schrödinger's wave mechanics. We focus on Einstein's efforts to understand the curious way in which two identical quantum systems, such as two photons, lose their separate identities in a phenomenon now known as "quantum entanglement." The clue to the riddle came in 1924 in a paper by a previously unknown Indian physicist, S. N. Bose, who showed that elementary particles like photons obey a new quantum statistics, meaning that, literally, one must count elementary particles in a different way from the way in which classical physics counts things. When Einstein realized that quantum entanglement would be such a deep and lasting feature of the quantum theory, he shifted from being a supporter of the new theory to being its most thoughtful critic.

Outline

I. As soon as he introduced the idea of independent light quanta in 1905, Einstein noted that this way of modeling radiation was strictly valid only for the limiting case of very high-frequency radiation. In general, therefore, the assumption of the mutual independence of light quanta would not be strictly valid. Here was yet another fact about the microworld that made no sense from a classical point of view, because it violated the classical principle of separability.

- **A.** Seeking a way to represent the manner in which quanta would fail to exhibit mutual independence, Einstein in 1909 borrowed the idea of the interference of waves from field theories like Maxwell's electrodynamics. He suggested that each photon was accompanied by something like a wave field and that the interference of two such wave fields, when they overlapped, accounted for the nonclassical failure of independence of quanta. The result was a picture of photons as being "two faced." The higher the frequency of the photons, the more they appear independent of one another. The lower the frequency of the photons, the more they appear to interfere with one another.
- **B.** Not until after the development of Schrödinger's wave mechanics and Heisenberg's matrix mechanics in the mid-1920s would the precise nature of this nonclassical, two-faced behavior become clear, when Bohr introduced in 1927 the concept of complementarity in quantum mechanics. But already in 1909 Einstein had invented the idea that would later be known as wave-particle duality.

II. In 1913, Niels Bohr introduced the quantum model of atomic structure, in which electrons revolve around a tiny nucleus in discrete orbits, sometimes jumping instantaneously from higher, more energetic orbits to lower, less energetic orbits, or vice versa, with the emission or absorption of photons whose frequency or energy corresponds to the difference in energy of those orbits. Once again, the emerging picture of the quantum world was inconsistent with classical physics, which had no place for discontinuities like discrete electron orbits and instantaneous quantum leaps.

- **A.** In 1916, Einstein added another essential piece of the quantum puzzle by showing that one could derive the Planck formula for black-body radiation by assigning probabilities to the transitions—the quantum jumps—in the Bohr model of the atom.
- **B.** Though Einstein later lamented the seeming failure of classical determinism in quantum mechanics, he was himself partly to blame, thanks to his having first introduced the concept of transition probabilities.

III. A still more radical idea came in 1924 with the introduction of Bose-Einstein statistics. The Indian physicist S. N. Bose surprised Einstein with an elegant derivation of the Planck black-body radiation formula based upon a new kind of statistics for photons. Einstein realized that the idea could be extended to material particles, like electrons, as well, and he saw that it offered the first real clue about how both photons and, now, material particles are not strictly independent in the quantum realm.

- **A.** The basic idea is best illustrated with a simple diagram. We have two particles and two "boxes" in what physicists call the "phase space" of the particles, which we can think of as just spatial locations for the particles. We ask how we can distribute the two particles over the two boxes.

Bose Statistics

	Box 1	Box 2
Case 1	• •	
Case 2	•	•
Case 3		• •

Independent Molecules

	Box 1	Box 2
Case 1	A B	
Case 2	A	B
Case 3	B	A
Case 4		A B

Bose-Einstein statistics.

- **B.** According to classical physics, as in Boltzmann's statistical mechanics, there are four possibilities:
  1. Both particles A and B in Box 1.
  2. A in Box 1 and B in Box 2.
  3. B in Box 1 and A in Box 2.
  4. Both particles A and B in Box 2.
- **C.** If one follows standard practice in assigning equal probabilities to the four possibilities, thus a 1/4 probability to each, then likelihood of the two particles being found in the same box is 1/2, adding the probabilities for cases 1 and 4.
- **D.** But Bose and Einstein noticed that this way of arranging the cases is based on the assumption that the two particles are distinguishable, in the sense that one can attach labels to them that allow us to track them individually. What if we assume that the particles are indistinguishable and take away the labels? Then Cases 2 and 3 above collapse into just one configuration, and we are left with only three possibilities:
  1. Two particles in Box 1.
  2. One particle in Box 1 and one particle in Box 2.
  3. Two particles in Box 2.
- **E.** Assume equal probabilities now, meaning a 1/3 chance for each possibility, and the likelihood of the two particles being found in one box goes up to 2/3, adding the probabilities for Cases 1 and 3.
- **F.** This is an astounding result. Simply assuming that quantum systems are indistinguishable leads to the conclusion that two such particles are more likely to be found near one another than would be the case classically. Einstein and Bose had discovered a special case of the strangest of all facts about the quantum realm, a feature that we now call "quantum entanglement."
- **G.** It was soon discovered that there is yet another quantum statistics for indistinguishable particles, Fermi-Dirac statistics, which turns out to be the statistics obeyed by particles like electrons. Particles like photons obey Bose-Einstein statistics. But both kinds of statistics are equally nonclassical and equally fundamental in the quantum world.

IV. Many people quickly grasped some of the profound and radical implications of the new statistics.

- **A.** Einstein's extension of Bose's statistics to material particles stimulated the young Frenchman Louse de Broglie to postulate the wave nature of material particles.
- **B.** Erwin Schrödinger was now able to solve the mystery of discrete electron orbits in the Bohr model of the atom, and young Werner Heisenberg followed a different path to the same goal of developing a full-blown mechanics of the quantum world. Schrödinger quickly demonstrated that his wave mechanics and Heisenberg's matrix mechanics were mathematically equivalent formalisms.
- **C.** Max Born showed why the transition probabilities Einstein introduced in 1917 worked as they did and that those probabilities were brute, fundamental features of a new quantum world that was at its heart indeterministic.
- **D.** These four great discoveries, each recognized with a Nobel Prize, were stimulated directly by Einstein.

V. But starting in 1927, Einstein surprised his contemporaries by turning his back on his own creation; he became quantum theory's most penetrating and persistent critic. He couldn't abide a universe ruled by chance.

Suggested Reading:

Howard, "'Nicht sein kann was nicht sein darf.'"

Jammer, *The Conceptual Development of Quantum Mechanics.*

Kragh, *Quantum Generations.*

Questions to Consider:

1. In the Bohr model of the atom, when an electron jumps from one orbit to another it is said to do so instantaneously and without following a continuous trajectory in space from one place to the other, as if it just dematerialized in one place and instantly rematerialized in another without ever having been in between. Does that make any sense?
2. According to quantum mechanics all photons are indistinguishable from one another, likewise all electrons and other species of elementary particles. But how can indistinguishability—which seems to be something subjective, something in the eye of the beholder—have implications for the objective physical behavior of elementary particles?

Lecture Fifteen
Quantum Mechanics and Controversy

Scope: Einstein was one of the discoverers of the quantum theory, but after the mid-1920s he became its most forceful critic. He was not alone in having doubts about a theory that postulated a fundamental randomness in nature, the impossibility of measuring simultaneously the speed and position of an electron, wave-particle "duality," and mysterious long-range entanglements between seemingly distinct elementary particles—not to mention a possible disturbing effect of the observer on the observed. Some thought, wrongly, that the very notion of objectivity was under attack. We will seek to understand why quantum mechanics, even more than relativity, was and still is seen by many people to be an unforgivable affront to classical intuitions about physical nature.

Outline

I. After his breakthrough with Bose-Einstein statistics in 1924, and especially after the development of the first comprehensive mathematical formalisms for quantum mechanics, Einstein's doubts about the quantum theory began to grow.

- **A.** Two features of the quantum theory especially bothered Einstein.
  - **1.** The first was its implication that indeterminism was an objective, fundamental feature of the physical world.
  - **2.** The second was the quantum theory's implication that spatially separated systems, like two photons, did not always behave like mutually independent systems.
- **B.** The basic formalism of quantum mechanics was firmly established by the beginning of 1927, starting with Schrödinger's wave mechanics in 1925 and Heisenberg's matrix mechanics in 1926. Einstein's friend Born had added the probability interpretation of the quantum mechanical wave function. But in 1927 Heisenberg added an important footnote when he derived from quantum mechanics the Heisenberg uncertainty principle, which was an affront to the classical intuitions of many physicists. In mathematical terms, we say that the product of the uncertainty, or indeterminacy, in a measurement or description of a system's position, Δx, times the uncertainty in its momentum, Δp, must always be greater than a specific minimum value that depends on Planck's constant. So $\Delta x \Delta p \geq \hbar/2$, where $\hbar$ [h-bar] is Planck's constant divided by 2π.
- **C.** Another important footnote was added, also in 1927, when Wolfgang Pauli explained that curious new fundamental property of elementary particles called "spin," or intrinsic angular momentum.
- **D.** Another major development just getting off the ground in 1927 was quantum field theory, which is now the framework for all of elementary particle physics.

II. Einstein's most famous objection to quantum mechanics was that it implied a denial of the determinism that was a bedrock feature of all classical physics.

- **A.** In December of 1926 he wrote, in a famous letter to Born:

  > Quantum mechanics is very worthy of regard. But an inner voice tells me that this is not yet the right track. The theory yields much, but it hardly brings us closer to the Old One's secrets. I, in any case, am convinced that He does not play dice.

- **B.** By the early 1950s, Einstein was ready to concede that indeterminism might be with us to stay, but for a long time he seemed to think that objective scientific knowledge was possible only if it described phenomena in a deterministic way.
- **C.** Einstein was one of the first physicists to ask whether the quantum mechanics of Schrödinger and Heisenberg might be developed further by adding what today we call "hidden variables," which were heretofore unknown properties of quantum systems, knowledge of which might enable us to make completely deterministic predictions of the systems' behavior.
- **D.** The deep reason for Einstein's commitment to determinism might be found not in his physics but in his theology and his moral philosophy.

III. Einstein was troubled by quantum indeterminism, but he was even more troubled by the quantum entanglement that he now recognized was a fundamental and unavoidable feature of the quantum mechanical description of nature.

- **A.** The word "entanglement" was first introduced by Schrödinger in 1935 in the wake of the Einstein-Podolsky-Rosen argument, but the feature of quantum mechanics named by the word was already well understood in 1927.
- **B.** In quantum mechanics, the joint state of any two or more previously interacting or indistinguishable systems is not just the aggregate of the separate states; in a very clear way, the whole is more than the sum of its parts.

C. After the work of Schrödinger and Heisenberg, the conclusion could no longer be avoided that quantum entanglement would violate the classical principle of separability. But Einstein tried to avoid it, because of his commitment to his own general theory of relativity, which builds the principle of separability into its basic field ontology of space-time points.

D. Entanglement violates the classical principle of separability, according to which the joint state of any two spatially separated systems is just the product of the states of the separate systems: $\Psi_{12} = \Psi_1 \otimes \Psi_2$.

IV. Einstein's skepticism only deepened as the further implications of quantum mechanics were explored in the next few years. As if the failure of determinism were not enough of an affront to Einstein's classical intuitions, it was followed by Heisenberg's indeterminacy or uncertainty principle, and next came Bohr's complementarity interpretation of quantum mechanics.

A. The Heisenberg indeterminacy principle says that in the quantum realm there are fundamental limitations on the precision with which one can describe quantum systems. It asserts that quantum systems literally do not possess simultaneously sharp values for "conjugate parameters" like position and momentum.

B. Bohr's complementarity interpretation of quantum mechanics goes further and asserts that relationships such as those embodied in the Heisenberg uncertainty principle are generic features of scientific knowledge in the quantum domain. According to Bohr, one can speak meaningfully of a property of a quantum system only in situations where, in principle, it is possible to measure or observe that property. The "measurement context," as Bohr would say, fixes the bounds of that about which one can speak objectively.

C. Position and momentum are complementary in the sense that they are mutually exclusive but jointly necessary for a complete description. The ultimate reason for this curious state of affairs is that in the quantum realm, the system being observed or measured and the system responsible for the measurement (including, perhaps, a human observer) cannot be represented as mutually independent systems.

V. Late in 1927, Einstein and Bohr met at the Solvay Congress in Brussels. It was the first of two major showdowns between these two giants, the next occurring at the 1930 Solvay meeting. On each occasion, Einstein sought by the use of clever thought experiments to exhibit what was, to him, so deeply troubling about quantum mechanics. But on each occasion, after long hours of debate, Bohr was able to find a flaw in Einstein's reasoning.

A. The most important of these thought experiments was the one Einstein produced at the 1930 Solvay meeting, called the "photon box" thought experiment. Einstein imagined that a box filled with electromagnetic radiation (photons) was suspended by a spring so that it could be weighed and was equipped with a shutter that could be opened by a timer attached to a clock. When the shutter is briefly opened, a photon escapes whose energy or time of arrival could be measured at some distant location. After the photon escapes we have the option of either (a) opening the box, reading the clock, and thus determining with arbitrary precision the time when the photon was emitted or (b) leaving the box closed, weighing it, and thus (via Einstein's own principle of mass-energy equivalence) determining with arbitrary precision the energy of the emitted photon. It would appear that one has a violation of the version of the Heisenberg uncertainty principle that asserts reciprocal uncertainties on measures of the energy and time of an event.

B. Bohr is said to have worked through the night and finally to have found that Einstein's mistake was his forgetting another one of his own important discoveries, namely, the effect of a gravitational field on clock rates. After the photon escapes, the box is a bit lighter and so rises a bit, meaning that it's a little bit further away from the Earth's surface and so experiences an ever-so-slightly weaker gravitational field, causing the clock to speed up by a tiny amount. The effect is minuscule but just enough to save the Heisenberg uncertainty principle.

C. Legend has it that Einstein was so stunned by the refutation of the photon box argument that he forever after gave up trying to disprove the Heisenberg uncertainty principle. In fact, Einstein had long before realized that there was no point in disputing the uncertainty principle. Instead, the whole point of the photon box experiment was to prove that quantum mechanics is an *incomplete* theory, not an incorrect one. This is the same argument the 1935 Einstein-Podolsky-Rosen paper would make.

Suggested Reading:

Baggott, *Beyond Measure*.

Beller, *Quantum Dialogue*.

Jammer, *The Conceptual Development of Quantum Mechanics*.

———, *The Philosophy of Quantum Mechanics*.

Lindley, *Uncertainty*.

Questions to Consider:

1. The Heisenberg uncertainty principle implies that the more definite a particle's momentum or speed, the less definite its position. Some interpret this as a limitation on how sharp our knowledge of momentum and position can be. Others say that the indefiniteness is an objective fact about the particle itself. Does it make any sense to talk about the objective indefiniteness of physical properties themselves?
2. In the photon box thought experiment, my choosing—after the photon has escaped—either to weigh the box or to open it and look at the clock makes a difference as to whether it's the photon's energy or its time of arrival at some distant location that is definite. But how can the distant photon "know" what choice I make and so have its properties and behavior affected by that choice?

Lecture Sixteen

Einstein in Princeton—The Lonely Quest

Scope: From 1933 until his death in 1955, Einstein the former world traveler never strayed far from his new American home in Princeton. There his household consisted of Elsa (who died in 1936) and his stepdaughter Margot and secretary Helen Dukas, both of whom outlived him by many years. Einstein's sister Maja Winteler-Einstein joined the household in the later 1930s and died in 1951. A simple daily routine was but little disturbed by the many visitors and various political crusades. Regular work at the Institute for Advanced Study was the centerpiece of Einstein's life. The main focus of that work was Einstein's lonely and ultimately fruitless quest for a unified field theory that would show both electromagnetism and gravitation to be structural aspects of an underlying continuous field, with elementary particles like the electron also being explained as just structural modifications of this field. That the rest of the physics community did not follow Einstein in this quest only confirmed Einstein's lifelong sense of himself as a "lone traveler."

Outline

I. During Einstein's last 22 years in America he was still very much engaged in the world of physics, and he built for himself in Princeton a cozy new circle of friends and colleagues. And yet the life and work of Einstein during these last years has a different feel. Einstein now more than ever followed his own course, this time on a path that he hoped would lead him to the promised land of a unified field theory.

- **A.** When Einstein settled in Princeton in 1933, his household consisted of himself; Elsa; and his secretary, Helen Dukas. Stepdaughter Margot joined them a little later; her sister Ilse died in Paris in 1934. Elsa died in 1936. Soon after, Einstein's sister, Maja Winteler-Einstein, arrived and lived with Einstein until her death in 1951. Einstein's elder son, Hans Albert, brought his family to the United States in 1938. Mileva died in Zurich in 1948, leaving their son Tete institutionalized in Switzerland.
- **B.** For the most part, Einstein lived a simple life. There were a few hours of work every day after a walk to his office at the Institute for Advanced Study, where in the 1950s his boss was J. Robert Oppenheimer, former director of the Manhattan Project. There was the company of a small circle of intimate friends.
  1. Einstein's colleagues at the institute included John von Neumann and Kurt Gödel, his best friend on the institute faculty.
  2. At Princeton University, Einstein was close to the economist Otto Nathan, who became co-trustee with Dukas of Einstein's literary estate.
  3. The unpretentious Einstein also got to know the African American community in Princeton surprisingly well.
- **C.** Einstein, Margot, and Dukas became U.S. citizens in 1940.

II. The hope for a unified theory of everything was not new and not exclusively Einstein's. At the end of the 19th century, just before the quantum and relativity revolutions, hope was high that Newton's mechanics and Maxwell's electrodynamics would soon be combined in one comprehensive theoretical framework. And within just three years of Einstein's finishing work on the general theory of relativity, that hope revived among thinkers who again felt the pull of the idea that fundamental unity is the sign of deepest truth in physics.

- **A.** The first serious attempt at a unified theory after general relativity was the work of Hermann Weyl, who took his degree at Göttingen under the mathematician David Hilbert and went on to teach at the ETH in Zurich, where he and Einstein were colleagues for a time.
- **B.** In the process of generalizing Einstein's field equations, he stumbled on a new, deep principle of symmetry called "gauge invariance."
- **C.** Einstein rejected Weyl's unification of gravitation and electromagnetism, largely because he was bothered by a fundamental feature of the theory called "the path dependence of length."

III. Stimulated by the challenge of Weyl's theory, Einstein soon took up the task himself, though at first only in an episodic way. When in 1927 he finally turned his back on quantum mechanics and committed to the unified field theory program, Einstein's particular goal was to unite electrodynamics and gravitation in a framework defined by general relativity.

- **A.** Most important in this task was the commitment to the idea of continuous field-like structures evolving deterministically in a space-time embodying the principle of separability. The contrast with entangled, nondeterministic quantum mechanics was intentional. No discreteness. No quantum jumps. And as in general relativity itself, fundamental particles were to disappear in favor of structure in space-time.

B. Einstein and his collaborators tried many ideas, such as modifications of the symmetries in general relativity or the introduction of complicated topological structures in space-time—like the Einstein-Rosen bridges that were the precursors of today's wormholes.

C. The goal as Einstein defined it was an impossible one, if only because of the fact that by the mid-1930s it was becoming clear that there were additional fundamental forces in nature beyond gravity and electromagnetism. Most physicists thought that Einstein's quest was wrongheaded, betraying a failure to understand the new quantum mechanics and its extensions into Paul Dirac's relativistic theory of the electron or quantum field theory.

D. A further problem bedeviling Einstein (and some efforts still today to construct a theory of quantum gravity—efforts such as string theory) was that he was doing physics at such a deep level and so far out on the edges of our understanding that it might be impossible, in principle, to extract from a unified theory any implications testable for ordinary laboratory or observation means.

IV. But Einstein was undeterred by even such obstacles. His reputation was secure, and he could risk failure on a scale unaffordable to a younger physicist.

A. Einstein's particular conception of a unified field theory no longer attracts a following, but the larger dream of unification, of a theory of everything, is once again very much alive. Important progress has in fact been made in the form of electroweak theories, which show how to unify electromagnetism and the so-called weak nuclear force. Still further unification is promised by what is called now the "standard model" in particle physics, which unites electromagnetism and the weak nuclear force with the strong nuclear force. Gravity is still not part of the picture in the standard model; there are exotic new ideas for how to add it to the mix, from string theory to what is called "loop quantum gravity."

B. In his quest for a unified field theory, Einstein stood apart from most of the physics community, but on the outside is where Einstein wanted to be. In the 1930s and 1940s in Princeton, where he created a quiet and eccentric academic life, he was still a well-known figure. But in his heart and mind Einstein was always alone. As he said in 1930:

> I am truly a "lone traveler" and have never belonged to my country, my home, my friends, or even my immediate family, with my whole heart; in the face of all these ties, I have never lost a sense of distance and a need for solitude.

Suggested Reading:

Goenner, "On the History of Unified Field Theories."

Isaacson, *Einstein: His Life and Universe*, chaps. 15, 19.

Parker, *Einstein's Dream*.

Regis, *Who Got Einstein's Office?*

Vizgin, *Unified Field Theories in the First Third of the 20th Century*.

Weinberg, *Dreams of a Final Theory*.

Questions to Consider:

1. Imagine that you were living in Princeton in the early 1950s and passed Einstein on the sidewalk as he walked home in the afternoon from the Institute for Advanced Study, seemingly lost in thought. Would you have asked for an autograph or would you have respected his privacy?
2. Einstein devoted the last decades of his life to a search for a unified field theory. Is it right to expect all physical phenomena to be described by a single, complete, consistent theory? Is unification, as when Maxwell unified optics, electricity, and magnetism, a dependable indicator that one is getting closer to the deep truth about nature?

Lecture Seventeen
Is Quantum Mechanics Complete?

Scope: In 1935 Einstein and two collaborators, Boris Podolsky and Nathan Rosen, published what has since become the most frequently cited paper in the history of physics. Now known as the Einstein-Podolsky-Rosen, or "EPR," argument, the paper seeks to prove that quantum mechanics is an "incomplete" theory and hence not the last word in fundamental physics. We will seek to understand this subtle argument in nontechnical terms, focusing on the deep physical and philosophical assumptions upon which it is grounded. Foremost among these assumptions is what Einstein called the "separation principle," which turns out to be none other than the denial of quantum entanglement, the feature of quantum mechanics that so troubled Einstein already in 1924, with its denial of the independent realities of spatially separated elementary particles. We will see that the deep reason why Einstein insisted upon his separation principle is that he thought it was a necessary feature of his own general theory of relativity. It might turn out that this tension between quantum mechanics and general relativity is the main reason why to this day we still lack a consistent theory of quantum gravity. If that is so, it means that Einstein's doubts about quantum mechanics, even if not valid, were extremely farsighted.

Outline

I. As we noted in Lecture Fifteen, at the 1930 Solvay conference Bohr believed he refuted Einstein's last, best effort to exhibit the possibility of violations of the Heisenberg uncertainty principle by means of the photon box thought experiment. But disproving this central principle of quantum mechanics seems not to have been the real point of Einstein's critique.

- **A.** What that point was started to emerge more clearly when, in 1935, Einstein published what has since become the most frequently cited paper ever to appear in the *Physical Review*, a paper entitled "Can Quantum Mechanical Description of Physical Reality Be Considered Complete?"
- **B.** The paper starts with two general principles:
  - **1.** The completeness principle: For a physical theory to be complete, it must include an element corresponding to every element of physical reality.
  - **2.** The reality principle: If one can predict with certainty the value of some physical quantity for a system without disturbing the system in any way, then there exists an element of physical reality corresponding to that quantity.
- **C.** The strategy of the EPR paper was to show that there are elements of physical reality not accounted for by quantum mechanics, which would mean that quantum mechanics is incomplete.

II. Many of Einstein's physics colleagues were shocked to find their hero going public in this way with his doubts about quantum mechanics. But when Schrödinger, who also had growing misgivings about quantum mechanics, wrote Einstein a congratulatory note, he got an unexpected reply. Einstein said that Podolsky had actually written the paper, "for reasons of language," and that the paper had not turned out as he, Einstein, had intended. The argument he then sketched for Schrödinger and repeated in all subsequent publications about the issue differed strikingly from the EPR paper.

- **A.** Einstein's own argument also starts with two previously interacting systems whose properties become correlated thanks to principles like the conservation of momentum. But in place of the completeness and reality principles, Einstein asserts just one principle, which he calls the separation principle.
- **B.** It says, simply, that the real state of system A cannot be influenced instantaneously by anything one does to system B. (Recall that special relativity assumes that the speed of light is an upper bound on all physical processes.) Einstein soon realized that there were really two principles here:
  - **1.** Two spatially separated systems possess distinct, independent, real physical states. This is now commonly called the separability principle.
  - **2.** The real physical state of B cannot be changed instantaneously by anything one does to system A. This is now commonly called the locality principle.
- **C.** Einstein then argued as follows: Since system B possesses its own independent physical state that is not influenced by anything I do to system A, then in particular, whatever choice I make for a quantity to measure on system A—which means choosing to put A in contact with different kinds of detectors—has no effect on B's physical state. But quantum mechanics assigns a different state description to B, a different wave function, say, depending upon what quantity one chooses to measure on A. Thus, quantum mechanics assigns more than one different theoretical description to one and the same real state of system B, which could be so only if the state descriptions that quantum mechanics assigns are incomplete.
- **D.** Einstein's point is that if the separation principle is true, as he thinks it must be, then a quantum theory incorporating entanglement is fated to be incomplete.

III. Einstein stressed that the separation principle was deeply interwoven in the foundations of all classical field theories, like his own theory of general relativity or unified field theories; a field theory in effect treats every point of space-time as a separate, independent real system.

- **A.** Einstein first says that if we're going to do physics at all, we must begin by dividing nature at its joints, carving nature up into bits and pieces.
- **B.** If we assume the separation principle is true—that spatially separated systems have separate, independent real states of affairs that cannot be changed instantaneously by what happens in some other region of space—then it doesn't make any difference how we carve up nature, since any way of carving nature will produce an objective carving into mutually independent parts.
- **C.** By the early 1950s, Einstein was willing to give up even his desire for determinism if that was the price to pay to save his separation principle.

IV. For almost 30 years after the appearance of the EPR paper, debates about completeness and entanglement remained largely theoretical.

- **A.** New arguments aiming to show quantum mechanics to be incomplete were produced, the most famous one, after EPR, being Schrödinger's "cat paradox."
- **B.** Schrödinger's argument was compelling enough to embolden a growing number of skeptics about quantum orthodoxy to take up afresh Einstein's old quest for a hidden variables interpretation of quantum mechanics.
- **C.** Thanks to work on the revival of hidden variables theories, progress was finally made toward turning a theoretical question about completeness and entanglement into a question that might be settled in the laboratory.
- **D.** In 1964 John Bell, a theoretical physicist at CERN, proved that any "local" hidden variables theory would yield predictions for such things as polarization correlation that necessarily fell below some threshold value. He also showed that quantum mechanics necessarily yields predictions for photon correlations that rise above that same threshold.
- **E.** After more than 35 years of experimental tests of Bell's theorem, it now seems clear that—unless one is willing to give up on relativity at the micro level—one has little recourse but to accept the conclusion that quantum mechanics is incomplete and that entanglement is a real fact about the deep physical reality of the quantum world.
- **F.** On this point, Einstein was just plain wrong, but it was one of the most fruitful mistakes in the history of physics. Research into quantum entanglement has crossed the divide from physics to engineering, and today quantum entanglement is the basis of a steadily growing array of new technologies.

Suggested Reading:

Baggott, *Beyond Measure*.

Bohr, "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?"

Einstein, Podolsky, and Rosen, "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?"

Howard, "Einstein on Locality and Separability."

Jammer, *The Conceptual Development of Quantum Mechanics*.

———, *The Philosophy of Quantum Mechanics*.

Lindley, *Uncertainty*.

Questions to Consider:

1. When two more or less identical billiard balls collide, their identities don't merge into a single, indissoluble two-ball pair. So why should an interaction between two electrons or two photons give rise to an entangled joint state?
2. Is it really impossible to imagine a macroscopic object like Schrödinger's cat existing in an objectively indefinite state somewhere between being alive and being dead?

Lecture Eighteen

The Expanding Universe

Scope: Einstein's general theory of relativity is the theoretical framework for all contemporary work in cosmology. Black holes, the big bang, an expanding universe—all of these ideas were implicit in the fundamental equations of general relativity, the so-called field equations, even if Einstein himself did not take all of them seriously. For example, when "non-static" (that is, expanding or contracting) solutions of Einstein's field equations were first discovered, Einstein thought them absurd. Just look at the heavens: Do you see the stars moving farther apart? And so Einstein added an ad hoc term, the cosmological constant, to block such models of the universe. Within 10 years, Edwin Hubble did observe cosmic expansion, and a shame-faced Einstein had to admit his mistake. One of the great ironies in the history of science is that Einstein's cosmological "constant" has now made a comeback—not to block non-static cosmologies, but amazingly, to explain the greater-than-expected expansion of the universe that we now think is driven by the mysterious stuff called "dark energy."

Outline

I. The story of black holes begins early in 1916, only a few months after Einstein had completed his work on general relativity, when the first exact solution of the gravitational field equations was worked out by the German physicist and astronomer Karl Schwarzschild.

- **A.** This solution represented the structure of space-time in the vicinity of a centrally symmetric mass such as the Sun. But one curious feature of the Schwarzschild solution was immediately evident. It was that if a sufficiently large mass were confined within a sufficiently small radius, the resulting curvature of space would be so great that any matter or energy coming near enough to it would be sucked into the resulting cavity in space-time with no chance of ever emerging again. Since light falling into the cavity could not reemerge, such regions of space-time were eventually dubbed "black holes."
- **B.** For a long time, no one (including Einstein) took this possibility seriously. But the doubters were wrong. It took decades before the first observation evidence of black holes was obtained.
- **C.** Only very recently, within the last 20 years or so, have sophisticated new instruments like the Hubble Space Telescope provided the evidence that black holes are in fact quite common in our universe. Indeed, we now think that there is a massive black hole at the center of every galaxy, such as our own Milky Way galaxy.

II. One year later, in 1917, Dutch physicist and astronomer Willem de Sitter produced the first exact "cosmological" solutions for the Einstein field equations.

- **A.** Cosmological solutions represent not the structure of some limited region of space-time but the structure of a whole universe. The de Sitter solution was surprising, too, because it pointed to the possibility of non-static universes—universes that expand or contract.
- **B.** Einstein thought that the plain evidence of the senses—we don't see the universe expanding or contracting—made it clear that ours was a static universe. But the de Sitter solution made expansion or contraction so likely that Einstein felt himself compelled to modify the field equations precisely so as to block such solutions, by adding a term called the "cosmological constant."
- **C.** Einstein did this reluctantly, seeing the cosmological constant as a blemish on an otherwise beautifully simple theory. But cosmic expansion seemed to him such an absurd idea that he had no choice.
- **D.** It is ironic that only a few years later, the American astronomer Edwin Hubble discovered that, in fact, distant galaxies are receding from us with velocities proportional to their distance. Further work on non-static cosmological models by Belgian physicist-priest Georges Lemaître and Russian physicist Alexander Friedman, combined with Hubble's observations, persuaded more and more people that Einstein should have trusted the implications of the original, unmodified field equations. With a sigh of relief, in the early 1930s Einstein conceded his error and removed the cosmological constant.

III. Still more surprising implications of general relativity were to come. Two noticed by Einstein himself early on were gravitational lensing and gravity waves.

- **A.** Gravity waves occur when there is a sudden change in the distribution of matter in some region of the universe, as with a stellar collapse or a supernova.
- **B.** Gravitational lensing occurs because of gravity's ability to bend light rays. Just as a glass lens can refract light and magnify an image in a telescope, so gravity can bend light and create curious images.

IV. Within 15 years of the discovery of general relativity, through the work of Einstein, de Sitter, Friedman, Lemaître, and Hubble, it was a basically accepted fact that our universe is a dynamic place, not a static one.

- **A.** The big bang picture won the argument in 1965 when Arno Penzias and Robert Wilson detected what is known as the "cosmic microwave background radiation," a kind of cosmic white noise static that is a remnant of the intense explosion in which the universe is supposed to have begun.
- **B.** The next 30 years saw intense efforts to gauge the rate of expansion and to measure the average density of the universe so as to determine whether the expansion would go on forever or eventually slow down, perhaps leading to a re-collapse. The inflationary model has recently enjoyed stunning confirmation through ever-more detailed observations of the fine structure of the cosmic microwave background radiation.
- **C.** Within the last decade or so, two discoveries have rocked cosmology to its foundations.
  - **1.** The first is the discovery of what is called "dark matter," because it interacts gravitationally (and not electromagnetically) with ordinary matter made up of protons, neutrons, and electrons. Evidence suggests that dark matter makes up roughly 22% of the contents of the universe.
  - **2.** The universe is expanding at a rate that would be impossible if the universe consisted only of ordinary matter and dark matter. In order to explain the observed rate of expansion, we must also postulate something called "dark energy," which makes up about 74% of the universe.
- **D.** More progress has been made in physics in the last 100 or so years than in the preceding 2000 years, and general relativity is the theoretical tool that made possible all of these remarkable new discoveries. But in yet another irony of contemporary physics, general relativity is part of a body of physical theory that we now realize describes at best only 4% of what's in our universe.
- **E.** One can react with dismay, or one can react with excitement. Most physicists are excited, because what we have learned is that we have so much more still to learn. Those, like Einstein, who thrive on intellectual challenge and adventure have so much to look forward to.

Suggested Reading:

Hooper, *Dark Cosmos*.

Kennefick, *Traveling at the Speed of Thought*.

Kragh, *Cosmology and Controversy*.

Wald, *Space, Time, and Gravity*.

Questions to Consider:

1. Assume that the big bang model of the universe, which implies that the universe had a beginning in time (currently estimated to be between 13 and 14 billion years ago), has been well confirmed. Would the truth of this model of the cosmos have theological implications?

2. Some philosophers and scientists look toward physics someday reaching closure, having explained everything. But much of the history of physics is history of vast new realms and deep new phenomena being opened to view. Examples include when the discovery of X-rays and radiation led us into the heart of the atom and, now, the discovery of dark matter and dark energy showing us that our best current physics describes no more than about 4% of the universe. Do you think that it's reasonable to expect explanatory closure in science?

Lecture Nineteen

Einstein and the Bomb—Science Politicized

Scope: One version of the story of 20th-century physics holds that a pure, disinterested quest for wisdom was transmuted in the 1930s, after the discovery of nuclear fission, into a devil's compact, as physicists rushed to build the ultimate weapons of war. But the real history is more complicated. Already in World War I, scientists on both sides of the conflict redirected their research to military ends, research on poison gas—on both sides—being only the most famous of many examples. Still, something important did happen in the 1930s and 1940s, for by the end of World War II, physics and other sciences (also physicists and other scientists) were drawn far more deeply into the political realm than had ever been the case before. Big science grew dependent upon government funding, including defense-related funding. And scientists found themselves in front of microphones and cameras, trying to inform the public—and behind closed doors, trying to advise presidents, prime ministers, and premiers. Einstein played a pivotal role in moving science out of the laboratory and into the public arena.

Outline

I. If Einstein ever harbored illusions about science being above politics, those illusions were shattered shortly after he moved to Berlin in 1914. World War I broke out just weeks later, and especially in Germany, many prominent scientists redirected their research programs to war-related projects.

- **A.** A case in point is Fritz Haber, a chemist who was already famous as the inventor of the Haber process for the artificial production of ammonia. After the war began, the intensely patriotic Haber turned his attention to research on poison gas. Haber pretended that his aims were noble, that such a weapon of terror would actually shorten the war and reduce human suffering, but friends like Einstein were horrified.
- **B.** The phenomenon of science in service to war was neither a new one nor exclusively a German one. In the United States, the National Academy of Sciences was created by Abraham Lincoln in 1863 to provide the government with technical advice during the Civil War, and the National Research Council was created by Woodrow Wilson in 1916 to facilitate research on technologies like sonar for detecting submarines. In World War I, the allies were quick to retaliate against the Germans with their own poison gas weapons.

II. After World War I, it might still have been possible for a few years for theoretical physicists to believe that, while engineers and chemists could be enlisted to make weapons, fundamental theoretical research was above the fray.

- **A.** It had occurred to some thinkers that Einstein's linking of mass with energy might some day find a military application, since even a tiny mass was now seen to have locked within it a tremendous energy. But nearly everyone thought the prospect so remote as to be meaningless.
- **B.** As research on nuclear physics accelerated in the early 1930s, however, a once-distant prospect began to look more and more real. When Otto Hahn and Fritz Strassmann finally detected nuclear fission in their Berlin laboratory late in 1938 and their former collaborator Lise Meitner, then a refugee in Sweden, provided the conclusive interpretation of those results, the theoretical physics world knew that such innocence as it might once have possessed was gone.
- **C.** Scientists outside of Germany, many of them Jewish refugees from Germany and central Europe, rightly feared the possibility of a German atomic bomb. One reaction was pressure for a voluntary moratorium on publishing work on nuclear fission, a truly extraordinary step for a physics community once deeply committed to the principle of free and open communication in science.
- **D.** Another reaction was Einstein's signing the famous letter to President Roosevelt in 1939 that warned of the threat from Germany and led ultimately to the creation of the Allied atomic bomb project.
- **E.** At about the same time, the German atomic bomb project was established under the leadership of Werner Heisenberg. There was still more than enough physics talent in Germany to justify the fear being felt elsewhere.

III. The Manhattan Project was, by orders of magnitude, the largest scientific and technical project ever undertaken. Many millions of dollars were spent, and thousands of scientists and engineers were employed. The sheer scale of the project and the fact that it was successful permanently changed the role that science plays in society.

- **A.** After the atomic bombs were dropped on Hiroshima and Nagasaki, the physicists who built the bomb realized that they now bore a moral responsibility different in kind and degree from any they had borne before.
- **B.** Equally significant in the long run was how the success of the Manhattan Project permanently changed the way science is funded and organized.
- **C.** Most scientific research before World War II had been carried out by individual scientists or small teams of scientists, and funding had come mainly from the universities or research institutes that employed those scientists.

D. But after World War II, new models for the organization and funding of research were developed. This was the era of what came to be called "big science," epitomized by giant government laboratories where often hundreds of scientists gathered together to do a single experiment with a large and expensive piece of equipment like a cyclotron.

E. Even the research done back in a university laboratory was now most likely to be funded by the Department of Defense or the National Science Foundation, which was created in 1950 to coordinate federal government funding of basic scientific research.

   1. With the government now picking up the tab for scientific research, new questions arose about the direction of scientific research. Proposals for funding had to be evaluated by committees of one's scientific peers.

   2. The question naturally arose whether agencies like the National Science Foundation should now take an active role in deciding how fundamental research was to be steered in the future.

F. In the Cold War climate of the late 1940s, 1950s, and beyond, much of the research done with military funding was also classified. No longer was it taken for granted that all scientific knowledge was to be open and freely shared, the exclusive property of no person or nation.

G. The need for high-quality scientific advice during the Cold War also earned for scientists a role at the highest levels of government, a fact made clear when in 1957 President Eisenhower created a cabinet-level position of presidential science advisor.

IV. Einstein was by no means the only engine of change, nor did he set out deliberately to make political the physics he loved for its beauty and detachment from the everyday and "merely personal." And yet he, as much as anyone, made it happen.

A. The August 1939 letter to Roosevelt will always stand as the clearest marker of change in the relationship between science and the state.

B. The impact of the letter was due in part to the way Einstein had put his scientific reputation to work in the service of political goals like Zionism, pacifism, and world government.

C. Einstein was capable of effecting change because of his prestige and notoriety as a thinker and advocate on a far larger stage than that of physics alone. Is that a good thing? That's a question for each of us to ponder by our own lights.

Suggested Reading:

Beyerchen, *Scientists under Hitler*.

Frayn, *Copenhagen*.

Isaacson, *Einstein: His Life and Universe*.

Jungk, *Brighter than a Thousand Suns*.

Rhodes, *The Making of the Atomic Bomb*.

Sayen, *Einstein in America*.

Questions to Consider:

1. In 1939, Leo Szilard proposed a voluntary moratorium on publishing work on nuclear fission, in order to prevent technical information from reaching German bomb scientists via openly published scientific articles. Was that a good idea? Would you, today, endorse voluntary moratoriums on publishing research that might help terrorists produce weapons of mass destruction?

2. Einstein later came to regret having written the letter in 1939 that led to the development of the Manhattan Project and the atomic bomb. Do you think that he acted rightly at the time?

Lecture Twenty

From the Manhattan Project to the Cold War

Scope: In 1939, Einstein signed a letter to President Franklin Roosevelt that launched the American atomic bomb project. At the time, Einstein thought this step thoroughly justified by the risk that Germany might develop an atomic bomb first and use it to tyrannize the world; a deterrent was needed. After World War II, however, Einstein came to regret this act as perhaps his greatest mistake. It is ironic that the Einstein who instigated the Manhattan Project was deemed a security risk by the FBI—because of his leftist politics—and so was not asked by the army to work on the project, though he did some more modest war-related work for the navy, work having nothing to do with the bomb. When the bomb was used without warning against largely civilian targets in Japan, Einstein was horrified, and no cause drew more of his energy in the last 10 years of his life than the effort to rein in the worldwide race in atomic and nuclear weapons. One of his very last public acts, the "Russell-Einstein Manifesto" of 1955, is seen by some historians as the first step toward serious international cooperation in arms limitation.

Outline

I. Einstein was not the first physicist moved by a sense of deep moral responsibility to try to limit the harm that might be done by the atomic bomb. In the summer of 1945, scientists involved in bomb research attempted to persuade the government not to use the bomb in a surprise attack against Japanese civilian targets. The most important of these attempts was the "Franck Report," which was prepared under the direction of the refugee German Jewish physicist James Franck at the University of Chicago, where the Metallurgical Laboratory functioned as an important part of the Manhattan Project.

- **A.** The report weighed the long-term political implications of a surprise attack, concluding that a demonstration of the bomb in front of Japanese observers might suffice to bring the war to an end and would also make more likely postwar international cooperation in the management of atomic energy.
- **B.** The report never reached its intended audience, its circulation and the solicitation of additional signatures being blocked by those in charge of the Manhattan Project.
- **C.** The Franck Report also asserted an obligation for scientists, acting as scientists, to take part in public debates about how the products of their research will be used.

II. When news of the Hiroshima bombing reached Einstein, he immediately saw the new threat posed by the atomic bomb and the responsibility that scientists like himself bore for trying to make the world safe from this horrible new technology of war.

- **A.** True to his convictions, Einstein set to work as a world leader of the movement to prevent a new arms race. No task consumed more of his time and attention during the last decade of his life.
- **B.** Einstein led and supported organizations like the Emergency Committee of Atomic Scientists and the Federation of Atomic Scientists (soon renamed the Federation of American Scientists). The latter helped establish the *Bulletin of the Atomic Scientists*, whose purpose was to put before the public reliable information about the science of atomic weapons.
- **C.** Einstein warned those who took comfort from an American monopoly on atomic weapons that such a monopoly would not last long. He was proven right when the Soviets exploded their own Hiroshima-scale bomb on August 28, 1949.

III. With the revelation of the successful Soviet A-bomb test, the terms of the debate about international control shifted dramatically. In the United States, the immediate effect was to intensify the push for the development of a new and more powerful weapon known as the hydrogen bomb, or "H-bomb."

- **A.** The bombs dropped on Hiroshima and Nagasaki, like the bomb tested by the Soviets in 1949, were of a kind known as "fission" (or "atomic") bombs, which release energy by splitting the nuclei of heavy atoms like uranium or plutonium.
- **B.** Hydrogen (or thermonuclear) bombs are known as "fusion" bombs. They release energy by combining the nuclei of light elements like hydrogen, helium, or lithium.
- **C.** Unlike fission bombs, there is no theoretical upper limit on the power of a fusion bomb.

IV. From the start, the development of the hydrogen bomb was controversial from a moral as well as technical point of view. Einstein joined in the public call to prevent the development of the hydrogen bomb.

- **A.** One of many occasions was an interview he taped in February 1950 for the premier of a new television show on NBC hosted by Eleanor Roosevelt.

B. Einstein warned that the hydrogen bomb brought with it the possibility of annihilating all life on Earth.

C. He also warned of the dangers of an uncontrolled arms race and of a concentration of financial power in the military, foreshadowing Eisenhower's warning about the "military-industrial complex" 11 years later.

V. While not as famous as Einstein, J. Robert Oppenheimer, the leader of the Manhattan Project, had by the late 1940s become a trusted advisor at the highest levels of government. But as the pressure to build the hydrogen bomb intensified, he openly began to voice his reservations.

A. To those like Edward Teller who were intent on building the hydrogen bomb, Oppenheimer's opposition was an unforgivable sin.

B. What happened next was like a Greek tragedy: Oppenheimer's opponents renewed rumors about his alleged flirtation with the Communist Party, and at the conclusion of a hearing into his loyalty on June 29, 1954, his security clearance was revoked.

C. Humiliated and barred from the corridors of power, Oppenheimer was broken psychologically. Einstein was outraged.

VI. Einstein's own struggle against the madness of nuclear weapons continued to the end of his life.

A. One of Einstein's last acts before his death in April 1955 was to join British philosopher Bertrand Russell in issuing a manifesto calling upon all nations of the world to abolish war, as the only way to avoid universal nuclear annihilation. The manifesto was drafted by Russell and was not released until July 9, 1955, almost three months after Einstein's death, but it had Einstein's full support.

B. In what came to be known as the "Russell-Einstein Manifesto," the authors argued that a nuclear war would be different from all previous wars because of the immense destructiveness of multi-megaton hydrogen bombs and the uncontrollable collateral effects, such as radioactive fallout. With all-out nuclear war, they argued, there was the possibility of the complete destruction of all human life. The abolition of war was, in their view, the only option.

C. The Russell-Einstein manifesto is credited with having helped to call into existence a series of conferences that brought together scientists from many nations, including the Soviet Union, China, Britain, France, and the United States, for private discussion about the risks of atomic war. The idea was that a basis for international understanding could be created by forging simple human-to-human ties within a scientific community fractured by the Cold War.

D. These "Pugwash" conferences are widely credited with having helped to create the ties that made possible the Limited Test Ban Treaty of 1963, the first of what became a long series of treaties that finally brought some measure of international control to the arms race and, with it, the chance of peace and security that Einstein himself did not live to see.

Suggested Reading:

Einstein, "Atomic War or Peace."

Isaacson, *Einstein: His Life and Universe*, chaps. 22, 24.

Jungk, *Brighter than a Thousand Suns*.

Rhodes, *Dark Sun*.

Sayen, *Einstein in America*.

Wang, *American Science in an Age of Anxiety*.

Questions to Consider:

1. The Franck Report strongly endorsed the idea of the scientist, acting as a scientist—not just a private citizen—in the political arena, seeking to control the way the products of scientific research are used. Einstein believed the same and was very active in seeking to control nuclear weapons. Do you think that this is the right principle, or do you think that the scientist's responsibility ends at the laboratory door?

2. Einstein strongly opposed the development of the hydrogen (or fusion) bomb. He believed that even if the Soviet Union developed the hydrogen bomb, the U.S. arsenal of atomic bombs would be a sufficient deterrent or defense, and that because of the potentially unlimited destructive potential of hydrogen weapons, their development would carry the world across a moral boundary that we dare not cross. Do you agree?

Lecture Twenty-One
A Lifelong Commitment to Social Justice

Scope: Settling into his new American home in the mid-1930s, Einstein threw himself into the effort to find jobs for the many, mainly Jewish, refugees from Nazism. But he found in the United States a new challenge in the form of racism. He lent his name to many organizations combating racial prejudice and lynching. He lectured at predominantly African American colleges, he made the soprano Marian Anderson a guest in his Princeton home when she was denied a room at Princeton's Nassau Inn, and he spoke up forcefully when his friend Paul Robeson had his U.S. passport taken away in the early 1950s. Socialism was another cause Einstein took up in the United States, especially after World War II, when Cold War fears fueled an anti-communist witch hunt that made professionally and personally risky the expression of even moderately leftist political opinions.

Outline

I. When Einstein settled into his new home of Princeton, New Jersey, late in 1933, he was sobered by the realization that even here anti-Semitism was a problem, in the form of quotas and quiet social prejudice. But it was racism of another kind that loomed still larger in Einstein's new American home.

- **A.** Even before his move to the United States, Einstein was recruited by African American historian, educator, and activist W. E. B. Du Bois to pen a letter about the dangers of racial prejudice for the 21st anniversary edition of *The Crisis*.
- **B.** After his move to the United States, Einstein devoted surprising public and private efforts to the cause of combating racial prejudice and promoting civil rights, as with his joining groups like the American Crusade to End Lynching.
- **C.** In 1946 Einstein accepted an honorary degree from Lincoln University in Pennsylvania, where he gave a lecture for physics students. Afterward, he was entertained at the home of Professor Laurance Foster, where he met six-year-old Julian Bond, son of the university's president, Horace Mann Bond.
- **D.** Einstein's involvement in the cause of civil rights included friendships with prominent African Americans like actor and singer Paul Robeson and soprano Marian Anderson. But he was also known as a friend in Princeton's own African American community.

II. Simply advocating civil rights was enough to earn Einstein the "subversive" label and drew the attention of the FBI.

- **A.** Public expressions of concern about Einstein's politics predated his permanent move to the United States. In 1932, a group called the Woman Patriot Corporation sought to block the issuance of a visa to Einstein for one of his planned trips to Caltech.
- **B.** The FBI's interest in Einstein intensified in the early 1940s when the army sought a ruling in connection with possible war-related research. A biographical sketch provided by the FBI to the army played up false rumors about Einstein's alleged work on behalf of the Soviet Union. Einstein was denied clearance to work on development of the bomb, but the navy cleared him to do consulting work.

III. Einstein was by no means the only target of FBI scrutiny. The FBI had files on millions of people the agency regarded as potential security risks. In April of 1951, Hoover reported to Congress that he had 14,000 people on the "Det-Com," or Detention of Communists list.

- **A.** Fear of communist subversion and persecution in the name of protecting American security became epidemic in America well into the 1960s. Many lives and careers were ruined by what were often false charges of communist sympathies.
- **B.** To Einstein, it was all too eerily reminiscent of the slow but steady descent into fascism he had witnessed in Germany in the early 1930s, when people's fears were manipulated to pave the way for tyranny, and "reasonable" people stood by, believing that the democratic institutions of a civilized nation would protect people's civil liberties.
- **C.** Einstein counseled others to stand firm. When Brooklyn schoolteacher William Frauenglass was subpoenaed to testify before the Senate Internal Security Subcommittee in 1953, Einstein advised him to refuse cooperation on the grounds that submitting to such an inquisition would be "shameful" and "contrary to the spirit of the Constitution."

IV. Einstein demonstrated his own resolve in the face of hostile criticism in 1949 when he published the influential article "Why Socialism?" in the inaugural issue of *Monthly Review*.

- **A.** Einstein's socialism was that of the democratic left, which distinguished itself from the communist left by its deep commitment to constitutional, electoral procedures and gradual social reform.

B. In his thoughtful and densely argued 1949 essay, Einstein argued for a planned economy but warned that it carried with it the risk that an all-powerful bureaucracy could become as much of a threat to the rights of the individual as is the unchecked competitiveness of capitalism.

C. Einstein noted that democratic government under capitalism cannot be trusted to protect ordinary working people because political parties are financed or otherwise influenced by private capitalists who constitute an "oligarchy of private capital." The worst evil of capitalism, he wrote, was "the crippling of individuals."

V. Einstein was always clear and firm in condemning what was going on in Stalin's Soviet Union, but he was something of an uncomfortable ally to American socialist friends who were willing to seek temporary political gain by joining in the red-baiting of the McCarthy period.

A. In a letter to the American socialist leader Norman Thomas in March of 1954, Einstein described conditions in the Soviet Union as "abominable to the taste of modern civilized man," but added that "America is incomparably less endangered by its own Communists than by the hysterical hunt for the few Communists there are here."

B. He concluded the letter by drawing the parallel to Germany in the early 1930s, where slogans like the "communist conspiracy" were mainly used to make "entirely defenseless" those who lack judgment and courage.

Suggested Reading:

Einstein, "Why Socialism?"

Jerome, *The Einstein File*.

Jerome and Taylor, *Einstein on Race and Racism*.

Nathan and Norden, *Einstein on Peace*.

Rowe and Schulmann, *Einstein on Politics*.

Sayen, *Einstein in America*.

Stachel, "Einstein and the American Left."

Questions to Consider:

1. Einstein advised targets of political persecution during the McCarthy era, like J. Robert Oppenheimer and William Frauenglass, not to invoke Fifth Amendment protections against self-incrimination but simply to refuse to cooperate at all with investigative bodies, citing Gandhi's example of passive resistance. Do you think Einstein was right?

2. Why has our culture chosen not to remember Einstein's involvement with civil rights and the labor movement and his advocacy of socialism, or even his opposition to nuclear weapons, as much as it remembers his work in physics?

Lecture Twenty-Two
Cosmic Religion and Jewish Identity

Scope: When Einstein was born in 1879, German Jews had only recently been accorded full citizenship rights. Einstein's own early years were not marked by an overly strong sense of Jewish identity. That identity was something he really only discovered when living in Prague brought him into contact with an extraordinary Jewish community that included the likes of Franz Kafka. Einstein never was a practicing Jew, but by the early 1920s he was lending his support to the Zionist movement, though always careful to note that it was "cultural Zionism" that he supported. Einstein was never a member of a church or a synagogue and wrote many times that he did not believe in a personal God. But he also wrote often about what he termed "cosmic religion," by which he meant the view that the rational order of nature itself was something that inspired awe and humility akin to the religious spirit. He was strongly influenced by the 19th-century German philosopher Arthur Schopenhauer, who combined the philosophy of Immanuel Kant with the Hindu Vedantic spiritual tradition. Schopenhauer's version of the Vedantic tradition postulated an ultimate reality in which all is one, including all individuals and all peoples. This all-embracing, ultimate metaphysical reality was, for Schopenhauer and probably also for Einstein, the basis of a social ethic that emphasized cooperation and respect.

Outline

I. Einstein grew up in a world where strict Jewish ritual was not observed, and he grew up without an especially vivid sense of his Jewish identity.

- **A.** As a student in Zurich in the 1890s, the values he imbibed would have been more those of the Swiss Ethical Culture Society, which included among its members assimilated Jews such as Einstein's patron Gustav Maier.
- **B.** Einstein first came to see himself as a Jew when, in Prague in 1911–1912 and then in Berlin after 1914, he found himself in cities with large, thriving Jewish populations.
- **C.** By the late 1910s, Einstein's sense of Jewish identity had become an important part of his sense of self, though it did not trump his commitment to a universal human community.
- **D.** What Einstein most valued in his Jewish heritage was its emphasis on morality and the life of the mind.
- **E.** Einstein's respect for the complexity of moral life was nowhere more on display than in his complicated relationship with the Zionist movement.
  - **1.** Fearful of the consequences of extreme nationalism, Einstein was careful to endorse cultural, rather than national, Zionism.
  - **2.** His ultimate loyalty to his Jewish heritage is evidenced by tireless work on behalf of Jewish refugees and his support of cultural institutions like the Jewish National and University Library in Jerusalem, where his papers today are consulted by scholars from around the world.

II. Einstein had no conventional religious convictions, but at a comparatively young age he developed an attitude toward nature itself, or rather toward nature in its law-governed aspect, that can only be described as spiritual or religious. It was an attitude of awe and humility in the face of the riddle of the universe. If he believed in any God, it was the God of the 17th-century Dutch Jewish philosopher Baruch Spinoza.

- **A.** In contrast to his rationalist predecessor René Descartes, Spinoza believed there is really only one substance, God, with mind and matter being just "modes" or ways of appearing of that one substance. In Spinoza's "radical monism," God and nature are one.
- **B.** Spinoza's God is mind as well as matter, and Spinoza taught that all of nature is ruled by intelligible laws that determine all things in nature. This talk of law was meant to express the determinism that was a basic feature of Spinoza's metaphysics, as well as his belief that nature is, in principle, intelligible.
- **C.** Spinoza's radical metaphysical determinism minimized the role of purely voluntary action and individual moral responsibility. Einstein found solace in a picture of the world in which his own personhood is lost in the immensity of the universe that is the object of the scientist's study.
- **D.** Thus, Spinoza played a fundamental role in shaping Einstein's physics, his moral philosophy, and his theology.

III. The other thinker who had a great influence on Einstein's deepest metaphysical, moral, and religious views was the 19th-century German philosopher Arthur Schopenhauer.

- **A.** From the marriage of Kant and the Vedanta, Schopenhauer evolved the view that a deep reality in which all is one is hidden from us by the "veil of Maya."

B. On this side of the veil, nature appears to us individuated by the Kantian forms of space and time; determinism reigns, causality being one of Kant's a priori categories of the understanding.

C. On the other side of the veil, you and I are not separate individuals: We are integral parts of a social whole that comprises all of human kind; the suffering of one is the suffering of the whole, as is the joy.

D. In Schopenhauer's picture of the universe, you and I and Einstein are all on both sides of the veil, as separate individuals and as part of an inseparable universal community that the lucky few glimpse only now and then, most often through aesthetic experience, most particularly music.

E. No other serious philosopher of the 19th century so stirred the yearnings of artists and intellectuals to seek a realm beyond the everyday and the personal. Central to Einstein's concept of "cosmic religion" is just this moment of transcendence.

IV. The larger question of the relation between science and religion has a long and vexed history, and yet thinkers like Isaac Newton, Michael Faraday, and Arthur Eddington had no trouble reconciling the two.

A. The transcendent, the divine, in Einstein's theology is nature itself, though not nature dissected, ready for study in the laboratory. Einstein's concept of the divine bears comparison with the old Stoic notion of Logos, the universal reason in all of nature.

B. Einstein's cosmic religion bears a romantic spirit of transcendence, but it is very much a rationalist's religion.

Suggested Reading:

Einstein, "Science and Religion."

Isaacson, *Einstein: His Life and Universe*, chap. 17.

Jammer, *Einstein and Religion*.

Stachel, "Einstein's Jewish Identity."

Questions to Consider:

1. If Einstein had accepted the presidency of Israel in 1952, and if he had lived, say, a decade longer than he did, to 1965, would his leadership have made an important difference in the development of modern Israel?
2. Nature in its law-governed aspect—hence, nature as an object of rational scientific inquiry—was Einstein's God, much as it was Spinoza's God. Are there consequences beyond theology of Einstein's repudiation of the notion of a personal or anthropomorphic God?

Lecture Twenty-Three
Einstein and Modernity

Scope: More than any other figure, Einstein is our culture's symbol of modernity. His physics partly inspired and was otherwise part of a broader movement in the late 19^{th} and 20^{th} centuries that self-consciously repudiated classical antecedents and fragmented the unities upon which an earlier worldview was based, such as continuity in space and time and the presumption of there being always a single correct perspective. Einstein and other moderns like Monet and Picasso asserted a democracy of perspectives without denying a truth standing behind multiple perspectives. Einstein was especially worried about the mistaken inference from relativity in physics to relativism in morals. And, in the end, Einstein couldn't accept the physics of indeterminacy and discontinuous quantum jumps. In this sense, he was a rather reluctant modern.

Outline

I. In this lecture, we shift our focus from Einstein himself toward the larger cultural world that responded so strongly to Einstein and his physics. The century whose onset coincided with Einstein's graduation from the ETH is one that thought of itself as distinctively "modern," and the heralds of modernity quickly seized upon the work, the person, and even the name of Einstein as emblematic of the new.

- **A.** The critic Clement Greenberg's analysis of Modernism in painting suggests one possible principle of Modernism in the form of reflexive self-criticism. He sees in the art of Paul Cezanne, for example, a tendency for the painting to criticize the craft of painting itself by acknowledging that it's painted on a flat, rectangular canvas.
- **B.** Self-criticism of means, Greenberg notes, is a hallmark of Kant's critical philosophy, in which it's the very process of knowing that turns inward to assess its own nature and limits.
- **C.** If that's what modernity involves, then Einstein is definitely a modern, because for all his differences with Kant over space and time, he wholeheartedly agreed that philosophy and science must evince such critical self-awareness and self-reflection.

II. One place to look for ideas is to the list of principles of classical physics we discussed way back in earlier lectures when we were trying to understand what was essential to classical physics, against which the quantum and relativity revolutions were reacting.

- **A.** The first of the three fundamental principles of classical physics we identified was continuity. The idea was that all processes in nature were continuous, in the sense that one could analyze them into ever smaller steps without ever reaching some last atomic bits. The quantum revolution changed all that, as first Planck and then Einstein taught us that in all processes, change proceeded necessarily in a stepwise fashion through the exchange of discrete, fundamental "quanta" of energy.
- **B.** In the art world of the later 19^{th} century, one of Greenberg's quintessential moderns is Georges Seurat, whose signal contribution was pointillism. Our practiced, 21^{st}-century eyes cannot appreciate the impact of *Grande Jatte* when it was first exhibited in 1886, with the continuous unity of scene and vision fractured into thousands of discrete quanta of color. Both Einstein and Seurat have revealed the true microstructure to be quantized, discretized, and pointillized.
- **C.** Seurat discretizes a static scene in space. Discretization in time was the result of high-speed photography and movies.
  1. In 1877, English photographer Eadweard Muybridge used multiple coordinated cameras to break up motion into stills to answer Leland Stanford's question about whether the feet of a galloping horse are ever all off the ground at the same time.
  2. In 1891, Thomas Edison produced the "Kinetoscope" for individual viewing of moving pictures, and five years later came his "Vitascope" for projecting images before an entire room of viewers.

III. Unity of a different kind was fragmented in ways evocative of relativity. As part of his assault on the Newtonian concepts of absolute space and time, Einstein argued that measures of location, time, speed, distance, and duration are all "frame dependent," having meaning only with respect to a given frame of reference.

- **A.** In Einstein's universe, there is no one truth about distant simultaneity, but rather an infinity of truths corresponding to the infinity of possible perspectives associated with the infinity of possible inertial states of motion of the observer judging simultaneity.
- **B.** Compare this to what another of Greenberg's moderns, the French Impressionist painter Claude Monet, was doing in the early 1890s. Monet produced many different series of paintings, each having a single subject depicted in

different lights, at different times of year, at different times of day, and in different kinds of weather. For Monet, reality is not exhausted by any one perspective.

- **C.** "Perspective" here does not mean a state of motion of the observer, but otherwise the analogy with relativity runs deep. There is a single subject, for example the cathedral in the Rouen series, or one physical process in the case of the relativistic description of cosmic ray muons. That one subject or process presents a different face when differently regarded.
- **D.** Perspective is handled in yet another fashion by Georges Braque and Pablo Picasso in the style of painting later dubbed "analytical Cubism." In this case Einstein is invoked by name, even if the physics doesn't exactly fit. In paintings like Braque's *Man with a Guitar*, done in 1911–1912, multidimensionality is the key.
- **E.** The cubists' simultaneous presentation of multiple perspectives is more of an affront to classical, realist presumptions about representation than is the serial perspectivalism of Monet. Even more so than Monet, the cubists force the viewer to reflect on method and technique, which Greenberg identified as the hallmark of the modern in painting.
- **F.** A famous literary experiment in multiple representation also makes an explicit invocation of Einstein and relativity: Lawrence Durrell's *Alexandria Quartet*, published from 1957 through 1960. The first three novels—*Justine*, *Balthazar*, and *Mountolive*—provide three different spatial perspectives, and the fourth—*Clea*—a temporal perspective on a story of passion and intrigue set in Alexandria as World War II approaches.

IV. Whether perspective reveals or destroys a deeper, inner truth was a question much discussed in many cultural settings through the 20th century. Let's think about the question as it was discussed by Einstein and the philosophers he read.

- **A.** A famous debate in the first decade of the 20th century pitted the moderate conventionalist Poincaré against the radical conventionalist Édouard Le Roy, around the time of Einstein's miracle year of 1905 and Picasso's first steps toward Cubism with paintings like *Les Demoiselles d'Avignon* of 1907.
- **B.** The question debated by Poincaré and Le Roy was important: Must there always be among a set of alternative theories or a set of alternative possible conventions some common core, called the "universal invariant"—some central truth upon which all are agreed? Poincaré said "yes"; Le Roy said "no."
- **C.** Einstein sided with Poincaré. That there is and must be a universal invariant was for Einstein a point of fundamental importance. Einstein was very much annoyed by the fact that so many people misunderstood this basic point about relativity. Too many people emphasized the relativity of position, time, speed, length, and duration, ignoring the invariant structure underlying these frame-dependent measures.

V. Einstein seriously proposed in the early 1920s changing his theory's name from "relativity theory" to "invariant theory," precisely to emphasize that it was the invariant core that represented reality. One place in the public arena where the effects of this confusion about relativity were most apparent, and most worrisome to Einstein himself, was in the too-frequent move from relativity in physics to relativism in morals.

- **A.** In the United States, the charge that relativity in physics led to relativism in morals came frequently from conservative religious groups, both Catholic and Protestant.
- **B.** Many people spoke up in Einstein's defense against such charges, and the most effective was Einstein's friend and biographer Philipp Frank, whose book *Relativity—A Richer Truth* was published in 1950.

VI. Einstein himself was a reluctant modern whose own preferred framework for fundamental physics posits as its basis a space-time continuum and deliberately repudiates the discreteness central to the quantum world. Einstein discovered all of the quantum craziness, but in the end he couldn't accept it.

Suggested Reading:

Everdell, *The First Moderns*.

Frank, *Relativity*.

Miller, *Einstein, Picasso*.

Vargish and Mook, *Inside Modernism*.

Questions to Consider:

1. To be "modern," after the models of Monet, Picasso, or Einstein, is to be aware of the difference that perspective or frame of reference makes in one's access to the reality that stands behind a multiplicity of perspectives. But if perspective always intrudes, if everything—even the invariant—is always viewed through a frame of reference, does it make any sense to continue to insist on there being an invariant or a deep reality?
2. When we assess the significance of Einstein's person and work for modernity, would his own tastes in art, literature, and music—about which little was said—be relevant?

Lecture Twenty-Four

The Sage of Princeton—Einstein the Icon

Scope: In spite of Einstein's wishes, the monuments were built. His picture is to be seen in every physics department in the world. Coffee shops and bagel restaurants bear his name. His image is the default emblem for genius. The biographies pour from the presses. His *Collected Papers*, being edited at Caltech and published by Princeton University Press, will eventually take up more than 20 volumes. That his legacy endures says much about us but, one wants to think, even more about him, and it all begins with his physics. With good reason, he stands out among physicists as a different kind of thinker. We conclude by asking how and why. Understanding the world that produced him and understanding the way his mind worked is the important task.

Outline

I. The first word that comes to mind when thinking about the example and legacy of Einstein is "genius." While we mean that label as an honor, too often our labeling someone a genius does more to obscure than to explain the person.

- **A.** Some of Einstein's distinguishing traits are obvious, even if not all that common. He had an unusual capacity for intense and sustained focus on a problem. He had an unusual knack for finding the perfect picture or thought experiment to express even the most arcane scientific ideas. He was uncommonly inventive, and he trusted his sense of simplicity, harmony, and beauty as a guide to scientific truth. And, contrary to popular mythology, he was a very good mathematician, even if his approach was a bit more intuitive than analytic.
- **B.** Other distinguishing traits are perhaps less obvious. Though Einstein was puzzled and more than a little embarrassed by his fame, he did reflect upon how his way of doing physics was different. More than anything else, he emphasized as crucial the independence of judgment that he displayed already as a young person.
- **C.** When it came to being a physicist, Einstein was quite explicit about his long and careful study of the philosophy and history of science as being most influential in making him an independent thinker. Something of an outlier in this as in so many things, Einstein was, however, not as different from his scientific contemporaries as he is from the typical scientist of today in being so well read in Kant, Hume, Spinoza, and Schopenhauer.
- **D.** Einstein repeatedly urged the inclusion of history and philosophy of science in the training of young physicists. In this respect, it is noteworthy that one very prominent contemporary physicist, Lee Smolin, has recently urged—in his book *The Trouble with Physics*—exactly the same revision in physics education as a remedy for what he sees as the lack of progress in fundamental physics over the last 30 years.

II. In his work in physics and in music, Einstein found an escape from the trials of everyday human life and his own personal moral failings.

- **A.** The Schopenhauer who gave Einstein a vocabulary for understanding this side of himself is often cited as one of the 19th-century precursors of Freud—one of the early explorers of the unconscious side of mental life. Were there unconscious roots of Einstein's creativity?
- **B.** Others who think Freud passé might be tempted to find the key to Einstein's mind in the mild form of autism known as Asperger's syndrome. That might explain the quick, penetrating mind and the seeming emotional coldness that Einstein too often displayed to those nearest him, but not the Einstein who was a good friend to many people, glittered in social settings, and excelled as a musician.
- **C.** My preference is to try, as best we can, to humanize Einstein—to see him as a being like us.

III. The sheer intellectual brilliance that we call "genius" is surely central to Einstein's iconic status, but the 20th century was populated with lots of brilliant scientists. Why did Einstein come to mean so much more?

- **A.** Einstein early on determined to put his fame to use in service to the humanitarian causes about which he cared so deeply. Our culture honors Einstein the foe of Nazism and racism, Einstein the champion of social justice and peace among nations, as much as it does Einstein the discoverer of the photon and of relativity.
- **B.** History has of late tended to focus more and more narrowly on Einstein the physicist. By comparison with his public image of 50 years ago, today one hears ever less about Einstein the crusader against nuclear weapons or the advocate of world government. One is more likely to hear about his vegetarianism than his ardent fight for civil rights, his membership in a labor union, or his deep commitment to socialism.
- **C.** The recent public obsession with new revelations about Einstein's infidelities, his illegitimate daughter, and his shabby treatment of Mileva and Elsa also displaces popular interest in Einstein the moral leader.

IV. To make vivid what Einstein the whole thinker and person once meant to a world in need of heroes, let's consider the story of Xu Liangying.

A. In 1937, Xu was a 17-year-old high school student in Hangzhou, China. He eagerly bought the Chinese translation of Einstein's 1931 collection of essays, *Mein Weltbild* (*The World as I See It*), when it was published in February of that year.

B. After the start of a promising career, in 1957 Xu was condemned as an "extreme rightist" and exiled to his village to work as a peasant laborer. While still in exile in 1962, Xu was asked to take on the task of translating Einstein's work into Chinese, as part of a state-directed program to make the works of "anti-Marxist" figures available for criticism.

C. The work took 14 years. Three volumes were published in 1976 through 1979. Xu was allowed to return from exile in 1978 and was restored to his position in the Academy of Sciences from which he had been expelled 21 years earlier, and his Einstein translations became an important source of inspiration for democracy advocates in China.

D. Xu became one of the most prominent advocates of democratization in China, and to honor his lifelong dedication to science and human rights, he was awarded the 2008 Andrei Sakharov Prize of the American Physical Society. In his acceptance speech, he talked about the influence of Einstein's work and example.

V. Einstein became an icon because we made him one. His striking image, his quick wit, his winning way with words—all of that made him "good copy" and played well in the new, electronically interconnected world.

A. Einstein's image conveyed a message, embodying the contradictions that made up his character. He was very much of this world, embroiled in all the sad and happy business of his day. But he was also not of this world, with a dreamy detachment of one who sought refuge in the abstractions of physics.

B. In choosing that Einstein as our icon, we project upon Einstein our own dissatisfactions with the world as we find it as well as our own hopes for something higher, a world where reason aligns with passion in service of a better future.

Suggested Reading:

Hu, *China and Albert Einstein*.

Isaacson, *Einstein: His Life and Universe*, chaps. 23, 25.

Sayen, *Einstein in America*.

Schweber, *In the Shadow of the Bomb*.

Smolin, *The Trouble with Physics*.

Questions to Consider:

1. What do we mean by labeling Einstein a "genius"?
2. What do the image, the example, and the legacy of Einstein mean to you?

Timeline

March 14, 1879 .... Einstein born in Ulm, Germany (in the state of Württemberg and the region known as Swabia or Schwaben).

June 21, 1880 .... Family moves to Munich, Germany (in the state of Bavaria), where Einstein & Cie., the electrotechnical business of father Hermann and uncle Jakob Einstein, is established.

November 18, 1881 .... Birth of sister, Maja.

October 1888 .... Enters Luitpold Gymnasium in Munich.

Fall 1889 .... Meets medical student Max Talmey, a frequent visitor for several years to the Einstein home who introduces Einstein to popular scientific books and the writings of philosopher Immanuel Kant.

June 1894 .... Family moves to northern Italy, where the family electrotechnical business is reestablished.

December 1894 .... Drops out of Luitpold Gymnasium and joins family in Italy.

October 1895 .... Fails entrance examination for Swiss Federal Polytechnic Institute (ETH) in Zurich, Switzerland; enters Aargau Cantonal School in Aarau, Switzerland.

Fall 1895–winter 1896 .... Falls in love with Maria Winteler, daughter of Aargau Cantonal School teacher Jost Winteler, in whose home Einstein is rooming.

January 28, 1896 .... Released from Württemberg citizenship.

October 1896 .... Enters ETH.

1897 .... Beginning of relationship with Mileva Marić.

July 28, 1900 .... Graduates from ETH.

Fall 1900–spring 1901 .... Fails to obtain position as assistant at the Swiss Federal Polytechnic; applies for but does not obtain assistant positions at numerous German, Dutch, and Italian universities.

December 16, 1900 .... Submits first paper to the *Annalen der Physik* (Annals of physics), the leading German physics journal; the subject is capillarity.

February 21, 1901 .... Obtains Swiss citizenship.

March 1, 1901 .... First paper published in the *Annalen*.

May 5, 1901 .... After six-week visit with parents in Milan, meets Mileva in Como, Italy, for a trip over the Splügen Pass to Switzerland, during which daughter Lieserl was probably conceived.

May–July 1901 .... Substitute teacher at the Technical School in Winterthur, Switzerland.

July 1901 .... Applies without success for teaching positions at technical schools in Burgdorf and Frauenfeld, Switzerland.

September 1901 .... Begins work as tutor at private school of Jakob Nüesch in Schaffhausen, Switzerland.

November 1901 .... Submits a dissertation to the University of Zurich.

December 1901 .... Formally applies for position at Swiss Federal Patent Office in Bern, Switzerland.

January 1902 .... Daughter Lieserl born at Mileva's parents' home in Novi Sad, Serbia.

February 1902 .... Moves to Bern, Switzerland, in anticipation of appointment at the patent office; apparently withdraws his dissertation at the University of Zurich.

April 30, 1902 .... Submits second paper to the *Annalen*; the subject is molecular forces.

June 23, 1902 .... Begins work at the patent office.

June 26, 1902 .... Submits first of three papers on foundations of statistical physics to the *Annalen*.

July 10, 1902 .... Molecular forces paper published in the *Annalen*.

September 18, 1902 .... First statistical physics paper published in the *Annalen*.

October 10, 1902 .... Father, Hermann Einstein, dies in Milan, Italy.

January 6, 1903 .... Marries Mileva Marić in Bern.

January 26, 1903 .... Submits second statistical physics paper to the *Annalen*.

April 1903 .... Beginning of the Olympia Academy, an informal discussion group with Maurice Solovine and Conrad Habicht.

April 16, 1903 .... Second statistical physics paper published in the *Annalen*.

September 1903 .... Daughter Lieserl possibly given up for adoption.

March 29, 1904 .... Submits third statistical physics paper to the *Annalen*.

May 14, 1904 .... Son Hans Albert Einstein born in Bern.

June 2, 1904 .... Third statistical physics paper published in the *Annalen*.

September 16, 1904 .... Patent office appointment made permanent.

March 18, 1905 .... Submits famous photon hypothesis paper, "On a Heuristic Point of View Concerning the Production and Transformation of Light," to the *Annalen*.

May 11, 1905 .... Submits paper on Brownian motion to the *Annalen*.

June 9, 1905 .... Photon hypothesis paper published in the *Annalen*.

June 30, 1905 .... Submits famous first paper on special relativity, "On the Electrodynamics of Moving Bodies," to the *Annalen*.

July 18, 1905 .... Paper on Brownian motion published in the *Annalen*.

July 20, 1905 .... Submits doctoral dissertation, "A New Determination of Molecular Dimensions," to the University of Zurich.

August 19, 1905 .... Submits revised version of doctoral dissertation to the *Annalen*.

September 26, 1905 .... Special relativity paper published in the *Annalen*.

September 27, 1905 .... Submits "$E = mc^2$" paper to the *Annalen*.

November 21, 1905 .... "$E = mc^2$" paper published in the *Annalen*.

January 15, 1906 .... Receives doctorate from the University of Zurich.

February 8, 1906 .... Revised version of doctoral dissertation published in the *Annalen*.

Fall 1907 .... Invents the "elevator" thought experiment and discovers the principle of equivalence.

1907–1911 .... Work with Paul and Conrad Habicht on the *Maschinschen* (the "little machine") for measuring tiny electrical quantities.

c. February 28, 1908 .... Appointed a Privatdozent (private lecturer) at the University of Bern.

Spring 1908 .... Teaches a course on the molecular theory of heat at the University of Bern.

Fall 1908 .... Teaches a course on the theory of radiation at the University of Bern.

July 9, 1909 .... Awarded first honorary degree, by the University of Geneva.

September 1909 .... Gives major invited lecture, "On the Development of Our Views Concerning the Nature and Constitution of Radiation," at the annual meeting of the Society of German Natural Scientists and Physicians at Salzburg, Austria.

October 2, 1909 .... Nominated for Nobel Prize for first time, by Wilhelm Ostwald.

October 1909 .... Moves from Bern to Zurich to begin new position as Extraordinary Professor for Theoretical Physics at the University of Zurich. Becomes the neighbor of Friedrich Adler.

July 28, 1910 .... Son Eduard Einstein is born in Zurich.

September 1910 .... Travels to Vienna to negotiate appointment at the Charles University in Prague (the German-language university in Prague, part of the Austro-Hungarian Empire); makes a special trip to meet the famous physicist and philosopher of science Ernst Mach.

February 10, 1911 .... Lectures in Leyden, the Netherlands; meets Hendrik A. Lorentz.

April 1911 .... Moves from Zurich to Prague to begin new position as ordinary (full) Professor of Physics at the Charles University in Prague.

October 30–November 4, 1911 .... Takes part in the first Solvay Congress in Brussels, Belgium; lectures on "The Current State of the Problem of Specific Heat."

c. February 1912 .... "Rotating disk" thought experiment; discovery of link between accelerating frames of reference on spatial curvature, thus also non-Euclidean geometry.

April 1912 .... Visits Berlin, where he meets leading physicists and falls in love with cousin Elsa Einstein Löwenthal.

July 1912 .... Moves from Prague to Zurich to begin new position as ordinary (full) Professor at ETH.

c. August 1912 .... Begins research notebook on general relativity and probably starts collaborating with mathematician Marcel Grossmann, former ETH classmate and now ETH colleague, on general relativity.

March 27, 1913 .... Lectures in Paris.

May–June 1913 .... Completion and publication of the early and mistaken version of general relativity, the so-called *Entwurf* theory, in a paper coauthored with Grossmann, "Outline of a Generalized Theory of Relativity and of a Theory of Gravitation."

July 1913 .... Nominated for membership in the Prussian Academy of Sciences; Max Planck, Walther Nernst, and their wives visit Einstein in Zurich to offer membership in Prussian Academy and probably also appointment at the University of Berlin, along with future Directorship of planned new Kaiser Wilhelm Institute for Physics.

July 1913 .... Niels Bohr proposes the quantum model of atomic structure.

August 1913 .... Hiking with Marie Curie in the Engadine region of eastern Switzerland.

March–April 1914 .... Moves from Zurich to Berlin to begin new positions at the Prussian Academy of Sciences and the University of Berlin.

June 1914 .... Separates from Mileva, who moves back to Zurich with their sons, Hans Albert and Eduard.

July 2, 1914 .... Gives inaugural lecture at University of Berlin.

July 23–August 3, 1914 .... World War I begins.

October 1914 .... Cosigns a manifesto, "To the Europeans," calling upon intellectuals especially to champion the cause of a united Europe, thus implicitly criticizing other leading German intellectuals for their support of German war aims.

June 28–July 5, 1915 .... Lectures on general relativity in Göttingen, Germany, and discusses general relativity with mathematician David Hilbert and colleagues.

November 4–25, 1915 .... Presents the general theory of relativity in its final form in four papers published in the *Sitzungsberichte* (Reports) of the Royal Prussian Academy of Sciences.

January–February 1916 .... First exact solution of field equations of general relativity by Karl Schwarzschild; discovery of the possibility of what later are called "black holes."

May 11, 1916 .... Publishes in the *Annalen* the comprehensive account of general relativity, "The Foundation of the General Theory of Relativity."

June 1916 .... Publishes first paper on gravitational waves.

July 1916 .... Introduces the concept of transition probabilities for emission and absorption of radiation by atoms; first time probability is assigned a fundamental role in atomic physics.

October 21, 1916	Austrian Minister-President Karl Graf von Stürgkh assassinated in Vienna by Einstein's old friend, Friedrich Adler, as a protest against Austrian policies in World War I.
1917	Publishes the classic popular book on relativity, *Über die spezielle und die allgemeine Relativitätstheorie* (*Relativity: The Special and General Theory*), that is translated into many languages and goes through 16 editions before Einstein's death.
February 1917	Introduces the famous cosmological constant to block non-static solutions of the field equations of general relativity.
September 1917	After being nursed for many months by cousin Elsa for many health problems possibly related to food shortages in Germany during the war, moves into Elsa's apartment.
April 1918	Begins debate with Hermann Weyl over Weyl's unified field theory for gravity and electromagnetism.
November 9, 1918	Germany surrenders, World War I ends, and revolutionary upheavals break out in Berlin and other parts of Germany as the Kaiser abdicates and a new republic (later known as the Weimar Republic) is established.
February 14, 1919	Divorces Mileva.
June 2, 1919	Marries cousin Elsa.
November 6, 1919	Formal announcement that general relativity's prediction of the bending of light near the Sun has been confirmed during the eclipse expedition in late May led by British astronomer and physicist Arthur Eddington.
February 20, 1920	Mother, Pauline (Koch) Einstein, dies in Berlin.
June 1920	Niels Bohr visits Einstein in Berlin (their first meeting).
August 24, 1920	Speakers at public meeting in Berlin Philharmonic Hall attack relativity for being "Jewish" physics and hence not properly "German." Part of broader upsurge in attacks against Jews.
September 23, 1920	Confrontation with prominent, Nobel Prize–winning experimental physicist and anti-relativity campaigner Philipp Lenard at the annual meeting of the Society of German Natural Scientists and Physicians at Bad Nauheim, Germany.
April 2–May 30, 1921	Visits United States for the first time, mainly to raise funds for the Hebrew University in Jerusalem on behalf of the Zionist movement; gives series of technical lectures on relativity at Princeton University, later published as *The Meaning of Relativity*.
August 1921–November 1923	Hyperinflation triggered by exorbitant war reparations payments cripples the Germany economy.
January 1922	First paper on unified field theory presented to the Prussian Academy.
March 28–April 10, 1922	Politically important visit to Paris to rebuild international scientific and intellectual relationships; lectures at the Collège de France and tours World War I battlefields.
April 1922	Joins the Committee of Intellectual Cooperation associated with the League of Nations.
June 24, 1922	German Foreign Minister Walther Rathenau, a prominent Jewish figure, is assassinated in Berlin; because of reports that he, too, might be targeted, Einstein drops out of the public eye for a while.
October 1922	Leaves on trip to Japan, with stops in Colombo, Singapore, Hong Kong, and Shanghai; gives several lectures in Japan.
November 9, 1922	Award of (deferred) 1921 Nobel Prize for Physics to Einstein is announced; award of 1922 prize to Niels Bohr is announced at the same time.
February 1923	Visits Palestine on return trip from Japan; lays the cornerstone for the Hebrew University of Jerusalem.
March 1923	Resigns from the Committee of Intellectual Cooperation in response to the League of Nations' ineffectiveness in the face of French and Belgian occupation of Germany's Ruhr industrial and coal mining region.

July 11, 1923 .... Nobel Prize lecture in Göteborg, Sweden.

June 1924 .... Resumes membership in Committee of Intellectual Cooperation.

July 1924–January 1925 .... Discovers Bose-Einstein statistics.

April–June 1925............................. Visits South America.

July 1925.. Werner Heisenberg discovers "matrix mechanics" formulation of quantum mechanics.

January 1926 .... Erwin Schrödinger discovers "wave mechanics" formulation of quantum mechanics.

March 1927 .... Werner Heisenberg discovers the indeterminacy or uncertainty principle.

May 1927 .... Fails in attempt to provide his own hidden variables interpretation of quantum mechanics.

September 1927 .... Niels Bohr announces his "complementarity" interpretation of quantum mechanics at the Volta conference in Como, Italy.

October 24–29, 1927 .... First major confrontation with Bohr over the adequacy of quantum mechanics at the Fifth Solvay Congress in Brussels, Belgium.

December 1927 .... Files patent with Leo Szilard for new refrigerator design.

March 1928 .... During lecture and vacation trip to Switzerland, suffers collapse and remains ill for weeks after his return to Berlin with what is diagnosed as pericarditis.

January 1929 .... Edwin Hubble provides observational evidence for the expanding universe.

September 1929 .... Moves into his much loved new summer house in Caputh, near Potsdam, about 40 km southwest of central Berlin.

1930 .... Publication of *Albert Einstein: A Biographical Portrait*, by Anton Reiser, a pseudonym for Rudolf Kayser, husband of Einstein's stepdaughter, Ilse.

October 20–26, 1930 .... Second major confrontation with Bohr over the adequacy of quantum mechanics at the Sixth Solvay Congress in Brussels, Belgium; "photon-box" thought experiment.

December 1930–March 1931.......... First research and lecture visit to the California Institute of Technology in Pasadena, California.

January 30, 1931 .... Attends premier of movie *City Lights* as guest of Charlie Chaplin.

April 1931 .... Removes cosmological constant from general relativity to accommodate expansion of the universe as proven by Hubble.

December 1931–March 1932.......... Second visit to California Institute of Technology.

July–December 1932 .... In response to a suggestion from the International Institute of Intellectual Co-operation, corresponds with Sigmund Freud about the causes of war; correspondence published as booklet, *Warum Krieg?* (*Why War?*)

August 1932................................... Appointment to the soon-to-be-established Institute for Advanced Study in Princeton, New Jersey.

Late fall 1932 .... Second son, Eduard, admitted for first time to Burghölzli asylum in Burghölzli, Switzerland, for treatment of psychiatric problems.

December 1932–March 1933.......... Third and final visit to California Institute of Technology.

January 30, 1933 .... Hitler sworn in as German chancellor; Nazis take power in Germany.

March 10, 1933 .... To protest Nazi seizure of power, Einstein announces that he will not return to Germany.

March 28, 1933 .... Resigns from the Prussian Academy of Sciences.

Spring–Summer 1933 .... Takes refuge under the protection of the Belgian government at Le Coq sur Mer, Belgium.

June 10, 1933 .... Delivers the Herbert Spencer Lecture, "On the Method of Theoretical Physics," at Oxford University.

October 3, 1933	Joins other prominent scholars speaking at a meeting in the Royal Albert Hall, in London, England, on behalf of organizations working to help refugees from Hitler's Germany.
October 17, 1933	Arrives in United States to take up new position at the Institute for Advanced Study in Princeton, accompanied by his wife Elsa, secretary Helen Dukas, and assistant Walther Mayer.
1934	Publishes *Mein Weltbild* (*The World as I See It*), his first major collection of popular writings on both scientific and nonscientific topics, edited by Rudolf Kayser, husband of stepdaughter Ilse.
May 1934	Elsa Einstein travels back to Europe, where her daughter Ilse Kayser is gravely ill. After Ilse's death, Elsa returns to the United States in September with her other daughter, Margot Marianoff.
May 15, 1935	Einstein publishes the famous "EPR" paper, "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete," coauthored by Boris Podolsky and Nathan Rosen, in the *Physical Review*.
July 8, 1935	Proposes the idea of "Einstein-Rosen bridges," later known as "wormholes," in a paper in the *Physical Review* coauthored with Nathan Rosen.
August 12, 1935	Purchases last residence at 112 Mercer St., Princeton, New Jersey.
October 15, 1935	Niels Bohr's reply to the EPR paper published in the *Physical Review*.
October 31, 1935	Meets Paul Robeson backstage at Princeton's McCarter Theatre after Robeson performs a concert of spirituals.
December 1935	Files patent with Gustav Bucky for design of a camera with automatic regulation of light intensity.
December 20, 1936	Elsa Einstein dies in Princeton, New Jersey.
April 16, 1937	Meets Marian Anderson when he invites her to be a guest in his home after she is refused a room at Princeton's Nassau Inn while in town for a recital at the McCarter Theatre.
1938	With coauthor Leopold Infeld, publishes *The Evolution of Physics*, a masterful history of physics for a popular audience.
June 13, 1938	Son Hans Albert Einstein and family arrive in the United States.
March 8, 1939	Sister Maja (Maria) Winteler-Einstein arrives in the United States.
August 2, 1939	Signs the letter drafted by Leo Szilard to President Franklin D. Roosevelt warning of the possibility of an atomic bomb and of possible German research on such a weapon; letter delivered to Roosevelt on October 11 by Alexander Sachs.
September 1, 1939	World War II begins when Germany invades Poland.
March 7, 1940	Einstein addresses a second letter to President Roosevelt urging action on atomic bomb research.
c. August 1940	FBI apparently starts a file on Einstein in response to a request from the United States Army for information on Einstein.
October 1, 1940	Receives United States citizenship in a ceremony at Trenton, New Jersey.
December 6, 1941	Decision to launch the major research and development project on the atomic bomb, later known as the "Manhattan Project."
December 7, 1941	Japan attacks Pearl Harbor, Hawaii; United States enters World War II.
December 2, 1942	First controlled atomic chain reaction under the direction of Enrico Fermi at Stagg Field, University of Chicago.
May 31, 1943	Einstein becomes a technical advisor to the Research and Development Division of the United States Navy's Bureau of Ordnance.
May 7, 1945	Germany surrenders; World War II in Europe ends.

July 16, 1945	First test of an atomic bomb, the “Trinity” test, Alamogordo, New Mexico.
August 6, 1945	Atomic bombing of Hiroshima, Japan.
August 9, 1945	Atomic bombing of Nagasaki, Japan.
August 15, 1945	Japan surrenders; World War II in the Pacific ends.
October 1945	Helps launch publicity campaign for Emery Reves’s book, *The Anatomy of Peace*, calling for world government.
May 3, 1946	Accepts honorary degree from Lincoln University, a predominantly African American university in Pennsylvania.
May 23, 1946	Accepts chairmanship of the Emergency Committee of Atomic Scientists.
February 20, 1947	Publication of Philipp Frank’s biography, *Einstein: His Life and Times*.
August 4, 1948	Former wife Mileva Marić dies in Zurich, Switzerland.
December 1948	Surgery on Einstein reveals an abdominal aortal aneurysm.
1949	Einstein’s intellectual autobiography, “Autobiographical Notes,” is published in *Albert Einstein: Philosopher-Scientist*, a collection of critical essays on Einstein’s work and replies from Einstein, edited by Paul Arthur Schilpp.
May 1949	Publishes article “Why Socialism?” in the inaugural issue of the journal *Monthly Review*.
August 29, 1949	First test of an atomic bomb by the Soviet Union, the “First Lightning” test, at the Semipalatinsk Test Site in Kazakhstan.
February 12, 1950	Appears on Eleanor Roosevelt’s NBC television program, “Today with Mrs. Roosevelt”; denounces atomic arms race, opposes development of hydrogen bomb, and calls for world government.
June 25, 1951	Sister, Maja Winteler-Einstein, dies in Princeton, New Jersey.
November 1952	Declines offer of Presidency of Israel after death of Chaim Weizmann.
May 16, 1953	In an open letter to Brooklyn, New York, teacher William Frauenglass, urges teachers and other intellectuals to refuse to testify when called before groups like the House Un-American Activities Committee; cites example of Gandhi.
April 14, 1954	Issues public statement supporting J. Robert Oppenheimer, former Director of the Manhattan Project, against allegations that he is a security risk.
March 15, 1955	Longtime friend Michele Besso dies in Geneva, Switzerland.
Spring 1955	Works with Bertrand Russell to organize what becomes known as the “Einstein-Russell Manifesto” opposing the nuclear arms race and calling for the peaceful resolution of international conflict; the manifesto is issued in London on July 9, 1955.
April 13, 1955	Abdominal aneurysm ruptures.
April 18, 1955	Dies in Princeton, New Jersey.

Glossary

a posteriori: In epistemology, the property of a judgment, statement, or item of knowledge's being posterior to or dependent upon experience.

a priori: In epistemology, the property of a judgment, statement, or item of knowledge's being prior to experience in the logical, not the temporal, sense of "prior." In Kant's philosophy, also implies that a judgment, statement, or item of knowledge is necessarily and universally true.

absolute space/absolute time: In classical physics, the privileged spatial frame of reference and time standard assumed to provide the objectively true measures of position, speed, length, duration, and distant simultaneity. The absolute spatial frame of reference was thought to coincide with the rest frame of the electromagnetic ether, or the "ether frame."

absorption spectrum: Sequence of discrete dark bands, ranging from lower to higher frequencies, in an otherwise full spectrum of colored light, produced when white light (or other forms of electromagnetic radiation) passes through an element, most commonly in a gaseous form, with the absorption of some of the energy in the light. The locations of the bands are distinctive and characteristic of different elements. The locations of the dark bands in the absorption spectrum for a given element are identical to the locations of the colored bands in the emission spectrum for that same element.

acceleration: In physics, a change in velocity, which is to say speed or direction of motion; alternatively, the rate at which such change occurs. Expressed in units of distance/time^2. Typically induced by the application of a force.

analytic: In epistemology and the philosophy of language, the property of a judgment or statement's being true (or false) in virtue of the meanings of the concepts or terms constituting the judgment or statement. More specifically, in Kant's philosophy, the property of a judgment's being true because the concept of the predicate is already contained in the concept of the subject.

angular momentum: In mechanics, the momentum associated with rotational motion.

atomic bomb (*see also* fission): A weapon that produces energy through the splitting of the nuclei of heavy elements. The type of weapon developed by the Manhattan Project during World War II and by the Soviet Union in 1949. There are theoretical upper bounds on the power of an atomic bomb because of the fact that a sustained fusion reaction requires the concentration of a "critical mass" of fissile material within a confined space, whereas the explosion itself disperses the material.

atomic spectra: The emission and absorption spectra associated with given species of atoms.

Bell's theorem: Theorem proved in 1964 by John S. Bell asserting that the predictions of any local hidden variable theory for certain types of quantum correlation experiments would have to satisfy an inequality, the Bell inequality, that is violated by the predictions of standard quantum mechanics. Subsequent experimental verifications of the standard quantum mechanical predictions are taken as evidence for the presence of a kind of non-locality in nature, perhaps related to quantum entanglement.

big bang: In cosmology, a model representing the universe's having arisen from an initial super hot and super dense state followed by continuing expansion up to the present. Name first invented as a term of derision by cosmologist Fred Hoyle, who defended an alternative steady-state model of the universe.

black-body radiation/black-body spectrum: Electromagnetic radiation associated with a black body, or more specifically, electromagnetic radiation contained in an enclosed black box and the energy spectrum of such radiation, with the energy intensity expressed as function of either wavelength or frequency. The black-body spectrum features a peak intensity, the location of which is related to the temperature of the body; the hotter the body, the more the peak shifts toward the high-frequency "blue" end of the spectrum. To say that the box is black is to say that its interior walls are perfect absorbers and re-emitters of electromagnetic radiation. The idea of the quantum was first discovered by Max Planck in the course of his search for a theoretical explanation of the black-body spectrum.

black holes: In general relativity and relativistic cosmology, a region of space-time where the mass density is high enough to induce such extreme curvature as to make it impossible even for light or other electromagnetic radiation passing beyond what's called the "event horizon" from ever again escaping the black hole. Stellar-mass black holes are now thought to be produced commonly by stellar collapse, and super-massive black holes are thought to be located near the center of nearly every galaxy. Called "black" because no light escapes. In fact, it is now thought that subtle quantum effects can lead a black hole to reradiate its matter and energy content, resulting in a gradual evaporation of the black hole.

Bohr model of the atom: Model of atomic structure proposed by Niels Bohr in 1913 in which negatively charged electrons revolve around a tiny, massive, positively charged central nucleus in discrete, stable orbits, jumping spontaneously and discontinuously from a higher to a lower orbit with the emission of a photon whose energy corresponds to the difference in energy of the two orbits or jumping spontaneously and discontinuously from a lower to a higher orbit with the absorption of a photon whose energy, likewise, corresponds to the energy difference between the two orbits. Provides a simple explanation for atomic spectra.

Boltzmann principle: In statistical mechanics, the principle relating the entropy or degree of disorder, S, of a system in a given state to the probability, W (in German, "probability" is *Wahrscheinlichkeit*), of that state, according to $S = k \log W$, where k is Boltzmann's constant.

Bose-Einstein statistics: The nonclassical quantum statistics obeyed by indistinguishable spin-1 particles like photons.

Brownian motion: The seemingly random motion of small particles suspended in a medium, such as pollen grains or dust particles suspended in water.

capillarity: In physics and chemistry, the phenomenon of one substance's being drawn toward another, as when a fluid is drawn up slightly along the sides of a tube or soaked up by porous paper.

classical physics: Conventional name for the combination of Newtonian mechanics and Maxwellian electrodynamics, possibly with the addition of thermodynamics and the kinetic theory of heat or statistical mechanics.

communism: A social and economic system with no class distinctions and common ownership of the means of production; also the political program promoting the creation of such an order. A variety of socialism. More specifically, after 1919, the program espoused by the political groups that affiliated themselves with the Third International or Comintern, which was under the effective leadership of the new Soviet Union and promoted the revolutionary transformation of existing social, political, and economic structures.

complementarity: Central concept in Niels Bohr's interpretation of quantum mechanics. In general, complementarity is the relationship between two things that are mutually exclusive but jointly necessary, typically in accounting for some phenomenon. More specifically in quantum mechanics, a relationship of complementarity obtains, according to Bohr, between parameters, like position and momentum, that cannot be simultaneously sharply defined. According to Bohr, this is because one can ascribe sharply defined values to such a parameter only in a context where it is possible to measure the parameter, and the contexts for measuring two such complementary parameters are mutually exclusive.

conservation laws/conserved quantities: In physics, various fundamental physical quantities, like energy and momentum in classical mechanics, are distinguished by being conserved, meaning that in any closed physical structure or process there can be no change in the total amount of that quantity. Thus, in an isolated physical system as described by classical mechanics, energy and momentum can be exchanged among the components, but the total energy and momentum of the system remain constant.

constructive theories: Einstein's term for theories that seek to represent phenomena by means of a constructive model of the phenomena.

continuity: In physics, the property of a structure or process involving there being no gaps. More specifically, but intuitively expressed, the idea that between any two points or stages in a structure or a process there will always be not just one, a few, or even a countable infinity of points or stages, but an uncountable infinity of points or stages, just as on the real number line there are between any two real numbers an uncountable infinity of other real numbers.

conventionalism: In epistemology and the philosophy of science, the view that some aspects of knowledge or elements of scientific theory that are not uniquely fixed by logic and evidence are adopted by convention or (perhaps unspoken or even not wholly conscious) agreement among the members of a given community, such as a scientific community. A famous example in the history of relativity is the allegedly conventional, physical definition of "straight line" as "path of a ray of light."

cosmological constant: Constant, Λ, added by Einstein to his gravitational field equations in 1917 to block non-static solutions of the field equations. Retracted by Einstein in 1931, after Edwin Hubble's observations of red shifts in the spectra of galaxies confirmed that our universe is expanding. Revived in recent years as part of a possible representation of dark energy.

cosmology: The study of the structure and formation of the universe as a whole as well as major components of the universe, such as galaxies.

covariance: In mathematical physics, the property of a mathematical structure's transforming like a vector under a coordinate transformation. Sometimes used informally and more generally as a virtual synonym for "invariance," the property of a structure's retaining its mathematical form under a transformation. Not to be confused with the notion of covariance in statistics.

Cubism: In painting, a Modernist art movement of the early 20th century pioneered mainly by Picasso and Braque, involving the decomposition of different perspectives on a subject or scene for the purpose of recombining these perspectival segments in an effort to present multiple spatial perspectives on a single canvas.

curvature: In geometry, and expressed intuitively, the feature of a non-Euclidean (non-flat) geometry corresponding to its embodying the kind of spatial relations seen (in the 2-dimensional case) on the surface of a sphere (positive curvature) or on a saddle-shaped surface (negative curvature). Can be generalized to 3-dimensional space or the 4-dimensional space-time of relativity theory. In general relativity, the presence of mass or energy in a region of space-time induces curvature, and that curvature, in turn, explains the motions of other massive bodies or the behavior of other energetic processes in that region, as with the bending of light near a massive body like the Sun.

dark energy: In cosmology, name for an unknown substance or process constituting roughly 74% of the total content of the universe that is postulated in order to explain an observed rate of expansion of the universe that is greater than what can be explained by ordinary big bang and inflationary cosmologies. Perhaps representable via Einstein's cosmological constant.

dark matter: In cosmology and particle physics, an as yet unknown form of matter, constituting roughly 22% of the total content of the universe, that does not interact electromagnetically with ordinary matter and manifests its presence mainly through its gravitational effects on ordinary matter and radiation.

determinism: The view that all processes and events in nature are rigidly controlled by exceptionless laws that fix all details of the processes and events. In other words, the view that for everything in nature, there is a cause.

diffraction: In physics, the bending of light waves or some other waves, typically where they interact with the sharp edges of a material object, as when waves pass through a narrow slit, resulting in interference between waves bent at different angles and, thus, the production of a diffraction pattern of alternating regions of higher and lower intensity.

diffusion: In physics and chemistry, the process whereby a substance moves, on average, from a region of higher concentration into a region of, initially, lower concentration, as when a dissolving substance is dispersed throughout a solvent or a gas spreads throughout a chamber.

dualism: In metaphysics, the view that there are two fundamental substances in nature (perhaps in addition to God). Mind and matter are often the two posited substances.

dynamics: Name both for physical phenomena involving the application of forces and for the scientific study of such phenomena, such as gravity's producing the fall of heavy objects near the Earth's surface or the orbital motions of the planets around the Sun.

Einstein-Podolsky-Rosen (EPR) argument: Argument proposed in 1935 by Einstein and coworkers Boris Podolsky and Nathan Rosen, purporting to demonstrate an essential incompleteness in quantum mechanics. Soon repudiated by Einstein, who proposed instead an argument to the same end based on the principle of separability.

electrodynamics: Name both for physical phenomena involving the dynamical effects of electricity and magnetism and the scientific study of such phenomena, such as electromagnetic induction producing an electrical current by the rotation of a conducting coil in a magnetic field.

electromagnetism: Name both for physical phenomena involving electricity and magnetism and for the scientific study of those phenomena.

electron: Negatively charged subatomic particle with a spin of ½, a mass of 9.1×10^{-31} kg, and a charge of -1.6×10^{-19} C (coulombs)—hence nearly 1/200 of the mass of the proton—but with a charge equal in magnitude but opposite in sign to that of the proton. In the normal configuration, an atom contains as many orbital electrons as there are positively charged protons in the nucleus. The atom's chemical properties are largely determined by the number and arrangement of outermost orbital electrons.

emission spectrum: Sequence of discrete bands of colored light ranging from lower to higher frequencies produced when light (or other forms of electromagnetic radiation) is emitted from an element, as with the burning of a substance. The locations of the bands are distinctive and characteristic of different elements. The locations of the colored bands in the emission spectrum for a given element are identical to the locations of the dark bands in the absorption spectrum for that same element.

empirical equivalence: In epistemology and the philosophy of science, the relationship between two theories that make exactly the same testable, empirical predictions.

empiricism: In epistemology, the view that all knowledge, or perhaps all knowledge other than logic and mathematics, is somehow grounded in experience, as opposed to being grounded on self-evident, necessary first principles. Empiricism typically emphasizes the contingency of knowledge claims, their being open to revision in the face of new and different experience, as when new experimental results overthrow an old theory.

energy: In physics, a property of physical systems typically defined as the ability to do work. Kinetic energy is a measure of the energy associated with matter in motion, represented in classical mechanics as $mv^2/2$, where m is a body's mass and v its velocity. Potential energy is the work done in moving a body against a force, as with the work done to raise a body in a gravitational field. Near the Earth's surface, for example, gravitational potential energy is represented by mgh, where m is, again, the body's mass, h is its height above the Earth's surface, and g is the acceleration due to gravity. Relativity theory famously postulates a deep connection between energy and the rest mass of an object, $E = mc^2$, where c is the speed of light in vacuum.

entanglement: In quantum mechanics and quantum field theory, the property of two or more indistinguishable or previously interacting systems wherein their joint state is not completely determined by the systems' individual states.

entropy (*see also* Boltzmann principle): In thermodynamics, a measure of comparative unavailability of a system's energy to do physical work. In statistical mechanics, a measure of the comparative disorder of a system's state, or a measure of the probability of the state—higher probability corresponding to greater disorder.

***Entwurf* theory**: Early, mistaken form of general relativity published by Einstein and Marcel Grossmann in 1913. Name taken from title of paper: *Entwurf* means "outline." Theory with restricted covariance properties.

epistemology: Philosopher's name for the study of the nature and limits of human knowledge.

equivalence principle: In general relativity, the assertion that the acceleration of a physical system or frame of reference is physically indistinguishable from the system or frame's being in a static, homogenous gravitational field.

ETH: One of Europe's preeminent technical universities, the Swiss Federal Polytechnic Institute (now commonly referred to by the initials of its German name as the ETH, the Eidgenössische Technische Hochschule).

ether: Hypothetical, quasi-material medium postulated as the carrier of the energy associated with a field, and the medium in which wavelike disturbances in the field are propagated. More specifically, the electromagnetic ether postulated in the 19^{th} and early 20^{th} centuries as the carrier of electromagnetic field energy and the medium in which electromagnetic waves are propagated. The luminiferous ether was the postulated carrier of light energy until Maxwell demonstrated that light is a species of electromagnetic radiation. Einstein's special theory of relativity is generally regarded as implying that there can be no electromagnetic ether.

Euclidean geometry: The geometry of a flat space, a space with zero curvature. The space in which classic geometrical claims hold, such as Euclid's parallel postulate, the theorem that the angles of a triangle sum to 180°, and the theorem that the ratio of a circle's circumference to its diameter equals π.

Fermi-Dirac statistics: The nonclassical quantum statistics obeyed by indistinguishable spin-½ particles like electrons.

field theory: In physics, a representation of physical systems and phenomena in terms of continuous mathematical structures defined over a 3-dimensional spatial manifold, a 4-dimensional space-time manifold, or a higher-dimensional manifold. Examples include classical Maxwellian electrodynamics, which takes as basic continuous spatially extended electric and magnetic fields, and general relativity, which takes as basic a metric tensor defined at every point of the space-time manifold. Quantum field theory typically associates not values of quantities but mathematical structures known as operators with points of space.

first law of thermodynamics: The assertion that energy is always conserved in thermal phenomena involving closed physical systems.

fission: The process involved in an atomic bomb, whereby the nucleus of a heavy element such as uranium or plutonium is split into the nuclei of lighter elements, with the release of neutrons and some of the binding energy of the original nucleus.

frame of reference: Point of view from which a physical description of phenomena is given. More specifically, in relativity theory, associated with a specific state of motion. Sometimes, but not necessarily, associated with a specific observer's state of motion. Sometimes also associated with a 4-dimensional (3 spatial, 1 temporal) set of coordinates used to describe phenomena, although the choice of a set of coordinates, though sometimes "natural" from a given observer's point of view, is in fact arbitrary and so often a matter of just convenience and convention.

frequency: In general, the duration of a cycle for a repeating process. In the case of a moving waveform, the number of times per second that a peak or trough passes a fixed point. In a moving wave, frequency, f, is inversely proportional to wavelength, λ (lambda). For light or other forms of electromagnetic radiation in a vacuum, $f = c/\lambda$, where c is the speed of light. In quantum mechanics, a photon has a frequency, denoted by the Greek letter nu, ν, that is related to the photon's energy, E, by $E = h\nu$, where h is Planck's constant.

fusion: The process involved in a hydrogen bomb, whereby the nuclei of light elements or their isotopes, such as hydrogen, deuterium, tritium, helium, or lithium, are combined to form heavier nuclei requiring less total binding energy than the sum of the binding energies of the original nuclei, thus releasing that excess binding energy.

galaxy: In astronomy and cosmology, a large, gravitationally bound collection of stars, gas, dust, and dark matter that typically, but not necessarily, has an elliptical or spiral structure. It is now thought that super-massive black holes also exist in the hearts of all, or nearly all, galaxies.

general theory of relativity: Second stage in the development of the theory of relativity, introduced in its final form by Einstein in 1915, extending the principle of relativity to physical descriptions of phenomena from the point of view of arbitrary frames of reference. More specifically, descriptions related to one another by arbitrary continuous and differentiable transformations, hence, in particular, accelerated frames of reference.

geodesic: The geometer's name for a line of shortest distance on a surface or in a space of arbitrary curvature. A generalization of the Euclidean notion of "straight line." For example, on a spherical surface (which is to say, a surface of constant positive curvature), the geodesics are all arcs of great circles, which are, like the Earth's equator or a line of longitude, circles of maximum circumference.

gravitational lensing: Process whereby massive objects in the universe, such as stars, galaxies, dust clouds, or dark matter, bend and refocus light and other forms of electromagnetic radiation from still more distant objects, often making visible to us objects otherwise too distant or too dim to be observed or objects blocked from direct view by the lensing structures.

gravitational mass: In classical, Newtonian mechanics and gravitation theory, the property of a body that scales its capacity to feel and exert gravitational attraction.

gravity waves: Periodic disturbances propagating in a gravitational field, typically as a result of a comparatively sudden, large perturbation such as a supernova.

Great Depression: A period of worldwide massive economic decline from the late 1920s to the mid- to late 1930s, its onset marked by the stock market crash of October 1929. In the United States, unemployment reached a peak of 25% in 1932.

habilitation: In German-speaking European countries, in effect a second doctoral thesis required in order to earn the right to function as a *Privatdozent*, or private lecturer at a university, a role roughly equivalent to an assistant professor in a North American university though traditionally compensated only by individual student lecture fees. Alternatively, the process of having the thesis accepted and earning the status of *Privatdozent*.

hidden variable theory: In physics, any of various proposed ways of supplementing or interpreting quantum mechanics in terms of heretofore unknown and perhaps, in principle, inaccessible variables, the values of which would, if known, fix precisely that which is left indeterminate in standard quantum mechanics.

holism: Generic term for the view that the elements of some structure form an indissoluble whole or that the combination of such elements is a unity different in kind from a mere collection of the elements, as in the motto "The whole is more than the sum of its parts." In epistemology or the philosophy of science, the view that individual hypotheses or beliefs are tested or assessed together, not one by one. In metaphysics, the view that the individual bits of some substance, such as matter, or the universe in its entirety form an indissoluble unity.

hydrogen bomb (*see also* fusion): A weapon that produces energy through the combination of the nuclei of light elements. There is no limit, in principle, on the power of such a bomb. Hydrogen bombs were first developed by the United States and the Soviet Union in the early 1950s.

Impressionism: In painting, a Modernist artistic movement of the late 19th and early 20th centuries that emphasizes not objective representation but the artist's individual impression of a subject or scene. Prominent representatives include Monet, Renoir, Pissaro, and Cezanne.

indeterminacy (*see also* uncertainty principle): In quantum mechanics, the inevitable, objective indefiniteness in the values of certain parameters, as with position and momentum as related by the uncertainty principle.

inertia: The tendency of a material body to remain in a given state of motion unless acted upon by an external force. In classical mechanics the inertial states of motion are (a) rest and (b) straight-line motion with a constant speed. An inertial state of motion is, in effect, an unforced and thus unaccelerated state of motion. In general relativity, an inertial state of motion would be motion along a geodesic trajectory in space-time.

inertial frame of reference: A frame of reference in an inertial, thus unaccelerated, state of motion.

inertial mass: In classical Newtonian mechanics, the property of a body that scales its capacity to resist changes in its state of motion.

inflation: In cosmology, a variant of the big bang model that postulates a very early phase of hyper-rapid, exponential expansion of the universe—the inflationary phase—thanks to which it can be assumed that all of what is today the observable universe arose out of what was once a small and thus causally connected universe or portion of the universe. Helps to explain the observed geometrical flatness of the universe on the macro-scale.

Instrumentalism: In the philosophy of science, the view that scientific theories generally—or perhaps just those elements of a theory purporting to name or refer to unobservable entities, properties, or structures—are to be regarded merely as tools or instruments for linking past experience to future experience, or for making predictions. Often opposed to **Realism**.

interference: In optics and other fields, the phenomenon of two coherent waves combining to form a new wave, or often, more specifically, the phenomenon wherein two coherent but out-of-phase wave trains, such as two out-of-phase light rays or two intersecting wave fronts spreading from different sources, combine to produce regions of high and low intensity—light and dark bands in the case of visible light—thanks to the two wave trains' or wave fronts' partly reinforcing (constructive interference) and partly cancelling one another (destructive interference).

interferometer: In physics, a device for combining two coherent rays of light for the purpose of detecting interference effects.

invariance: In mathematical physics, the property of an equation or mathematical structure's retaining the same mathematical form under transformations, as with the invariance of Maxwell's equations for electrodynamics under the Lorentz transformations. Thought by many physicists and philosophers of science to be a mark of that equation or structure's corresponding to a real physical aspect of nature, as opposed to a frame-dependent and hence merely relative aspect of a description.

isotope: Variant form of an element involving the addition or subtraction of neutrons to the nucleus.

kinetic theory of heat: In physics and mainly in the 19th century, the program of seeking an explanation of macroscopic thermal phenomena in terms of the motions of the microscopic atomic or molecular constituents of a substance, but typically without all of the mathematical tools deployed in statistical mechanics. In a sense, the precursor of statistical mechanics.

length contraction: In relativity theory, the apparent shrinking or shortening of a yardstick as judged from a frame of reference in which the yardstick appears to be moving, the shrinking occurring only in the direction of the yardstick's apparent motion. Applies not just to yardsticks but to any spatially extended physical system. Not a real physical contraction but a matter of perspective, and perfectly reciprocal. Judged from the point of view of the "moving" yardstick, a yardstick or other extended object in that other frame of reference would appear to be contracted by the same amount.

light principle: In relativity theory (which is based upon the relativity principle and the light principle), the light principle is the assertion that the speed of light is a constant independent of the state of motion of the source. Together with the relativity principle, the light principle implies that all observers in inertial frames of reference should see light moving with the same speed.

locality principle: In relativity theory, the assertion that no physical process (hence also no signal) can propagate with a speed faster than the speed of light. Implies that there can be no instantaneous physical interaction between spatially separated physical systems.

logical empiricism: In the philosophy of science, preferred name for the movement associated with the Vienna Circle and for the doctrines of that group. Prominent among these are such claims as that the only cognitively meaningful assertions are those that are either logically true or false or those that are empirically verifiable, and the related view that ethical and aesthetic judgments lack cognitive meaning.

logical positivism (*see also* logical empiricism): Alternate name for logical empiricism. Differs from positivism more generally in embracing logic and mathematics even though they are not empirical forms of knowledge.

Lorentz-FitzGerald contraction: A postulated real physical contraction of an object in the direction of its motion through the hypothetical electromagnetic ether, introduced originally in an effort to explain away the null result of the Michelson-Morely experiment without abandoning the notion of an electromagnetic ether.

Lorentz transformations: Mathematical equations employed in the special theory of relativity to relate a description of phenomena in one inertial frame of reference to a description in another. Maxwell's equations for electromagnetism have the property that their mathematical form remains invariant under the Lorentz transformations, as should all fundamental dynamical equations in a physics compatible with special relativity.

matrix mechanics: In physics, the version of quantum mechanics discovered by Werner Heisenberg in 1925. Observable physical magnitudes and the states of physical systems are represented by matrices.

McCarthy period: Common name for the period from the late 1940s through the mid-1950s in the United States during which Cold War–inspired, anti-communist witch-hunting (often employing agencies of government such as House and Senate investigative committees) and the persecution of individuals suspected of communist sympathies reached peak intensity. Named after Senator Joseph McCarthy of Wisconsin.

mechanics: Name for both physical phenomena involving matter in motion and the study of those phenomena. Frequently used to designate more narrowly what might more appropriately be called "classical mechanics," the theoretical perspective on matter in motion deriving from the work of Newton and refined in the 18^{th} and 19^{th} centuries in the work of Leonhard Euler, Joseph Louis Lagrange, William Rowan Hamilton, and Carl Jacobi.

metaphysics: Philosopher's name for the study of the fundamental nature of reality.

metric: In geometry and general relativity, and expressed intuitively, the standard whereby distance in a point-manifold, such as space-time, is judged. Closely related to the local degree of curvature.

metric interval: In relativity, also known as the "space-time interval." A generalization of the Pythagorean notion of distance in Euclidean geometry, incorporating also temporal distance. In special relativity the metric interval $\sqrt{(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2 - c^2(\Delta t)^2}$ is an invariant under the Lorentz transformations. In general relativity, the infinitesimal metric interval $\sqrt{g_{\mu\nu} dx^\mu dx^\nu}$ is an invariant under arbitrary continuous, differentiable coordinate transformations. In the latter expression, the indices μ and ν range over the 4 dimensions of space-time, and the expression as a whole is shorthand for a sum of the 16 terms obtained from all possible permutations of the values of μ and ν.

metric tensor: In differential geometry, and intuitively expressed, a mathematical structure encoding information about the curvature of a manifold, defined at every point of the manifold. More specifically, in general relativity, the mathematical structure encoding information about the local curvature of space-time. Tensors are generalizations of vectors.

Modernism: In art and literature, name for a cluster of schools and movements from the mid-19^{th} through at least the mid-20^{th} century that self-consciously repudiated dominant or received styles and conventions, often in professed allegiance with contemporary developments in science and technology. Sometimes more specifically characterized as involving deliberate, critical analysis of and reflection on artistic and literary production itself.

momentum: In mechanics, the product of mass and velocity.

monism: The view according to which all seemingly different kinds of substance are really only one, or aspects or modes of some one fundamental substance. There are different varieties of monism, such as Spinoza's view that both mind and matter are but modes of some one substance otherwise also identical with God and nature; or the view that matter is the only substance, a view sometimes denoted "materialism"; or the view that energy is the basis of all physical reality, a view popular among physical chemists in the 19^{th} century under the name "energeticism."

nebula: In astronomy and cosmology, a massive cloud of dust, plasma, or hydrogen gas. The term was once used in astronomy to name any large nonstellar object, before the distinctive nature of galaxies as collections of stars was discovered starting in the early 1920s.

neo-Kantianism: Philosopher's generic name for a wide variety of views arising in the mid- to late 19^{th} and early 20^{th} centuries claiming descent from the philosophy of Immanuel Kant in the late 18^{th} century. One prominent variety is Marburg neo-Kantianism, the philosophical tradition originated by Hermann Cohen and represented by Einstein's teacher August Stadler and by Ernst Cassirer. Marburg neo-Kantians sought to amend Kant by locating the a priori entirely within the realm of cognition and not in the realm of experience, where Kant had situated the a priori structures of space and time.

neutron: Electrically neutral subatomic particle with a spin of ½ and a mass of 1.7×10^{-27} kg. Isotopes of a given element differ in terms of the number of neutrons contained in the nucleus, the nuclei of all isotopes of a given element containing the same number of protons. Neutron number plays a major role in determining the comparative stability of the nucleus against some forms of radioactive decay and its susceptibility to processes such as fission. Neutrons, being electrically neutral, can penetrate a nucleus with comparative ease and therefore play a crucial role in inducing the fission that powers the atomic bomb and atomic reactors.

noumenal realm: In Kant's philosophy, the realm of things in themselves, as opposed to things as we experience them.

nucleus: The positively charged, comparatively heavy and tiny central part of an atom. Consists of protons equal in number to the atomic number of the corresponding element and neutrons in numbers typically ranging from the number of protons to as much as about 60% more than the number of protons (only the hydrogen nucleus lacks protons).

ontology: Philosopher's name either for the basic entities, processes, or structures in a given realm of nature; or in nature as a whole; or for the study of such entities, processes, or structures. In physical theory more specifically, the basic entities, processes, or structures assumed in a theory's description of phenomena, as with classical Maxwellian electrodynamics assuming a field ontology or the atomic theory's assuming a particle ontology.

pacifism: Opposition to war or violence in settling disputes. More specifically, promotion of peaceful, nonviolent means for resolving international conflict. Sometimes more specifically still, as in Europe in the 1920s, entailing opposition to the maintenance of standing armies or the promotion of strict limits on troop numbers and types of armaments.

perihelion: The point of closest approach to the Sun in a planet's orbit around the Sun.

phenomenal realm: In Kant's philosophy, the realm of things as we experience them, as opposed to things in themselves.

photoelectric effect: The process whereby electrons are emitted from a conducting surface, typically the surface of a metal, when it is illuminated by light or some other form of electromagnetic radiation, giving rise to an electrical current.

photon: Electrically neutral and massless subatomic particle with a spin of 1. Sometimes also called "light quanta," photons are the particle-like embodiments of electromagnetic radiation.

Planck's constant: Fundamental physical constant whose finite magnitude characterizes and fixes the scale of the discreteness in physical processes and structures that is a basic part of the quantum mechanical description of nature. An example is Einstein's discovery that electromagnetic radiation lives in the form of discrete, particle-like carriers of electromagnetic energy of magnitude $E = h\nu$, where ν (nu) is the frequency of the associated radiation and h is Planck's constant. The value of Planck's constant is roughly 6.6×10^{-34} Js (joule seconds).

Playfair's postulate: An equivalent form of Euclid's fifth or parallel postulate, enunciated in 1795 by Scottish mathematician John Playfair. Playfair's postulate asserts that given a line and a point not lying on that line, there exists through the given point one and only one line parallel to the given line. Helpful for understanding non-Euclidean geometries as deriving from the two different ways of denying Playfair's postulate, by asserting either that there are no parallels through the given point or that there are multiple parallels through the given point, corresponding to spaces of positive and negative curvature, respectively.

pointillism: In painting, a technique widely employed in the late 19th century in the work of painters like George Seurat, involving the use of many very tiny dots of color to create the appearance of continuous swathes and fields of color, often with a subtle mixing or blending of two or more colors.

positivism (*see also* logical positivism): In philosophy, the view that genuine knowledge is demonstrable by scientific means, or often more specifically, the view that genuine knowledge is empirical knowledge. In most cases a variety of empiricism, and typically inhospitable to metaphysics.

positron: Positively charged subatomic particle with a spin of ½, a mass of 9.1×10^{-31} kg, and a charge of 1.6×10^{-19} C (coulombs). The first known antiparticle. Its existence was predicted by Paul Dirac in 1928 and confirmed by Carl Anderson in 1932.

precession: In mathematics, a change in the direction of an axis.

principle theories: Einstein's term for theories built from "principles," which he regarded as mid-level, empirically well-confirmed generalizations, like the conservation of energy or the light and relativity principles, which serve as constraints on the search for more fundamental, constructive models of phenomena. According to Einstein, relativity theory was an example of a principle theory.

proton: Positively charged subatomic particle with a spin of ½, a mass of 1.7×10^{-27} kg, and a charge of 1.6×10^{-19} C (coulombs), hence nearly 2000 times more massive than the electron, but with a charge equal in magnitude but opposite in sign to that of the electron. The number of protons in the atom's nucleus determines the atomic number of the element.

quantum field theory: In physics, the body of theory that extends basic quantum mechanics to fields like the electromagnetic field and seeks to do so in a Lorentz covariant, hence relativistic, way.

quantum jumps: In the quantum theory, any process involving a sudden, random, discontinuous transition of a system from one state to another, as when, in the Bohr model of the atom, an electron suddenly jumps from a higher to a lower orbit with the emission of a photon, or from a lower to a higher orbit with the absorption of a photon.

quantum mechanics: In physics, the body of theory providing a detailed description of the state structure, dynamics, and observable properties of quantum systems like the electron, the proton, or the photon. Two specific forms of quantum mechanics are Schrödinger's wave mechanics and Heisenberg's matrix mechanics.

quantum theory: In physics, the generic term for theories or models, or the project of constructing such, that take as basic the quantum structure of the entities, processes, or structures involved.

radioactivity: General name for various processes by which an atomic nucleus decays with the release of radiation, often changing the nucleus into one of a different element. Principal modes of radioactive decay include (a) alpha decay, in which the nucleus emits an alpha particle, essentially a helium nucleus consisting of two protons and two neutrons, yielding a nucleus with an atomic number two less than the parent nucleus; (b) beta decay, in which the nucleus emits a beta particle, which is to say an electron, and an antineutrino, typically as a result of a neutron's converting into a proton, which yields a nucleus with atomic number one higher than the parent nucleus; and (c) the transition of a nucleus in an excited state to a less energetic state, with the release of a gamma ray, which is an extremely energetic form of ordinary electromagnetic radiation.

rationalism: In epistemology, the view that all knowledge or at least the most basic aspects of knowledge are grounded in self-evident, necessary first principles, perhaps after the model of a deductive science like Euclid's geometry, all of which was thought by Euclid to be derivable from five self-evident postulates. Rationalism typically emphasizes the enduring truth of knowledge so understood, immune to correction by new experience or observational evidence.

Realism: In the philosophy of science, the view that scientific theories—including those elements of a theory seemingly referring to unobservable entities, properties, or structures—aim to provide a true picture or representation of objective physical reality. Sometimes known by the more specific name "Scientific Realism." Often opposed to **Instrumentalism**.

red shift: In physics, the shifting of spectral lines toward the longer-wavelength/lower-frequency, red end of the spectrum, either as a result of a Doppler shift caused by the relative motion of the radiation source away from the observer or as a result of the radiation source's being in a gravitational field. Since energy is proportional to frequency for elementary particles like photons, a red shift is also a shift to a less energetic state of affairs.

relativism: In philosophy and morality, the view that knowledge or values are relative to a point of view, an individual, a class, a gender, a community, or some other group or interest.

relativistic cosmology (*see also* cosmology): The branch of cosmology in which models of the universe are constrained by having to be solutions of Einstein's general relativistic or gravitational field equations.

relativity principle: In mechanics and the theory of relativity, the assertion that the physical description of phenomena must look the same in any inertial frame of reference. In classical mechanics, the Galilean principle of relativity was asserted for all purely mechanical phenomena, such as the free fall of heavy bodies. In the special theory of relativity—where this is, along with the light principle, one of the two principles upon which the theory is based—the principle is asserted for both mechanical and electromagnetic phenomena.

rest mass: In relativity theory, the mass of an object as measured in the object's rest frame, which is to say a frame of reference in which the object is at rest.

scientific philosophy (*see also* logical empiricism): In the philosophy of science, a view closely associated with logical empiricism but somewhat more sympathetic to Realism. Espoused mainly by Einstein's Berlin friend and colleague Hans Reichenbach.

second law of thermodynamics: The assertion that entropy always tends to increase in thermal processes involving closed physical systems.

separability principle: The assertion that any two spatially or spatiotemporally separated physical systems possess their own independent, real physical states of such a kind that the joint state of the two taken together is determined completely by the separate individual states.

singularity: In mathematics and mathematical physics, a value of an independent variable at which a function is undefined. More specifically in general relativity and relativistic cosmology, a point or region where solutions to Einstein's general relativistic or gravitational field equations break down, as in the center of a black hole or at the origin of the universe in a big bang model. Some singularities are just artifacts of a choice of coordinates, but big bang and black hole singularities are thought to correspond to real aspects of physical structure in the relevant solutions to the field equations.

socialism: A social and economic system featuring worker and citizen participation in the control of economic arrangements; also, the political program promoting the creation of such an order. More specifically, after 1923, the program espoused by the political groups that affiliated themselves with the Socialist International, which promoted the democratic transformation of existing social, political, and economic structures. The political program of Social Democratic and Labor parties.

space-time: In relativity theory, the 4-dimensional manifold of point-events that constitutes the theory's basic ontology in the way of formulating relativity theory first invented by Hermann Minkowski in 1907 and then later adopted by Einstein. More informally, the 4-dimensional successor to the older, Newtonian notions of separate 3-dimensional space and 1-dimensional time. Relativity requires this amalgamated space-time structure because of the manner in which, say, the Lorentz transformations combine position and time in translating from one frame of reference to another.

space-time interval: ***see* metric interval**.

special theory of relativity: First stage in the development of the theory of relativity, introduced by Einstein in 1905 and restricted to the physical descriptions of phenomena from the point of view of inertial frames of reference, descriptions related to one another by the Lorentz transformations.

specific heat: In physics and chemistry, the amount of heat energy needed to raise a specific quantity of some substance (typically a mass of 1 gram) by a specific temperature difference (typically 1° Celsius).

spin: In quantum mechanics, an intrinsic property of elementary particles and systems like atoms composed of elementary particles. Closely related in terms of its observable manifestations, such as a charged body's response to a magnetic field, to the classical mechanical property of angular momentum (the momentum associated with a spinning massive body) but not involving any actual spinning in space. As a quantum property, spin always takes only discrete values, such as +1 and −1 one for photons (which obey Bose-Einstein statistics) and +½ and −½ for electrons (which obey Fermi-Dirac statistics). Moreover, since spin is a quantum property, components of spin measured along orthogonal directions (right angles to one another) obey a relation of mutual exclusion somewhat like the relation between position and momentum according to the Heisenberg uncertain principle.

statistical mechanics: In physics, the study of thermal and other, related phenomena (such as diffusion) not from a macroscopic point of view but from the point of view of the average, detailed behavior of the individual atoms and molecules composing a system. Statistics are employed because of the impossibility of determining and calculating the exact behavior of the many millions of constituent atoms and molecules.

stress-energy tensor: In general relativity, the mathematical structure encoding information about the mass and energy content at a point in space-time.

supernova: Massive stellar explosions produced as a result of either a sudden gravitational collapse or runaway nuclear fusion.

synthetic: In epistemology and the philosophy of language, the property of a judgment or statement's being true (or false) not simply in virtue of the meanings of the concepts or terms constituting the judgment or statement. More specifically, in Kant's philosophy, the property of a judgment's being true when the concept of the predicate is not already contained in the concept of the subject. More generally, a judgment or statement that asserts more than what is contained in the concept of the subject.

thermodynamics: Name both for physical phenomena involving the macroscopic thermal (heat-related) behavior of physical systems and for the scientific study of such phenomena.

thought experiment: An imaginary, often highly idealized, experiment conforming strictly to relevant scientific laws, typically for the purpose of assaying or demonstrating the implications of a theory or a scientific hypothesis.

time dilation: In relativity theory, the apparent slowing of a clock as judged from a frame of reference in which the clock appears to be moving. Called "dilation" because the slowing of the clock rate is equivalent to a lengthening of the interval between ticks of the clock. Applies not just to clocks but to any periodic process. Not a real physical slowing but a matter of perspective, and perfectly reciprocal. Judged from the point of view of the "moving" clock, a clock or other periodic process in that other frame of reference would appear to be slowed by the same amount.

transcendental: In philosophy, a term applied to Kant's philosophical project and its descendants, designating its characteristic posture of critically assessing the nature and limits of knowledge as a preliminary to seeking even purely philosophical knowledge, but also empirical scientific knowledge. Not to be confused with the concept of transcendence, meaning the state of being beyond the realm of everyday experience or, in a theological setting, the created world.

uncertainty principle: Also called "Heisenberg uncertainty principle." In quantum mechanics, the assertion that there are reciprocal limits on the definiteness in the values of conjugate parameters that can be ascribed to quantum systems, as with the famous relation between position, x, and momentum, p: $\Delta x \Delta p \geq h/4\pi$, where h is Planck's constant.

underdeterminationism: In epistemology and the philosophy of science, the view that knowledge or theory choice is not uniquely determined by logic and experience or by some specific set of empirical facts or observational or experimental results. Hence the view that for such sets of facts or results there will always be more than one theory equally compatible with those facts or results. Usually understood as a version of **conventionalism**.

unified field theory (*see also* field theory): In physics, name for a program of seeking or for specific examples of theories that explain separate forces, like gravity and electromagnetic forces, in terms of some one underlying field structure. Frequently used more narrowly to designate theories that employ the tools and structures of classical field theories akin to Einstein's general relativity or Maxwellian electrodyamics rather than quantum field theories.

Vedanta: Ancient Hindu spiritual tradition which aims at self-realization through knowledge of ultimate reality; embodied in the collection of writings called the Upanishads.

veil of Maya: An image from the Vedanta representing the boundary between the world as we experience and know it and deep reality, Maya being the deity who maintains the illusion of the phenomenal world.

verificationism/verifiability criterion of meaningfulness: In philosophy of science, a doctrine closely associated with logical empiricism, according to which the only cognitively meaningful assertions are those that are either logically true or false or empirically verifiable. Alternatively, the view that the only meaning of a statement that is not either logically true or false is comprised of the facts or experiences that would verify the statement, otherwise known as the statement's empirical meaning.

Vienna Circle: The most influential group of 20th-century philosophers of science, centered in Vienna in the 1920s and early to mid-1930s around the philosopher Moritz Schlick and including Rudolf Carnap and Philipp Frank. Claimed close connections to the philosophy of Ernst Mach. Defended a set of doctrines known by the name of "logical empiricism."

viscosity: In physics and chemistry, a fluid's resistance to flow.

wave mechanics: In physics, the version of quantum mechanics discovered by Erwin Schrödinger in 1926. The states of systems are represented by wave functions defined on an abstract configuration space, and physical magnitudes are represented by differential operators that take such wave functions as their arguments.

wavelength: In general, the length of the interval between two adjacent peaks or troughs in a wave form. In a moving wave, wavelength, λ (lambda), is inversely proportional to frequency, f. For light or other forms of electromagnetic radiation in a vacuum, $\lambda = c/f$, where c is the speed of light. In quantum mechanics, thanks to wave-particle duality, a wavelength is associated with every elementary particle, such as the electron, according to the formula $\lambda = h/p$, where h is Planck's constant and p is the particle's momentum.

wave-particle duality: In quantum mechanics, the assertion that all elementary systems and processes possess both wavelike and particle-like aspects, as with light's being representable in some situations as electromagnetic waves and in other situations as photons, or a beam of electrons' behaving like particles when they scatter after colliding with atoms or like waves when they exhibit electron diffraction.

Weimar Republic: Common name for the democratic constitution under which the German government operated from shortly after World War I until Hitler's seizure of power in 1933. By extension, a name for the period itself and the culture that flourished in Germany during those years.

world-line: In relativity theory, a continuous trajectory through 4-dimensional space-time representing the motion of a system.

X-rays: A highly energetic form of electromagnetic radiation, with a wavelength in the range of 10 to 0.1 nanometers. Capable of easily penetrating less dense forms of matter. Less energetic than gamma rays.

Zionism: Social and political movement of the late 19th century and 20th century calling for the creation of a Jewish national home and possibly a Jewish state in Palestine.

Biographical Notes

Friedrich Adler (1879–1960). Austrian physicist, philosopher, and political figure. Einstein's friend from student days in Zurich, other finalist for physics position at the University of Zurich in 1909 that became Einstein's first teaching job. Supporter of Ernst Mach's philosophy of science; German translator of Pierre Duhem's *Aim and Structure of Physical Theory* (1908). Son of Victor Adler, cofounder of Austrian Social Democratic Party. Assassinated Austrian Minister-President Stürgkh in 1916 as protest against Austrian war policy. Freed from prison after World War I.

Marian Anderson (1897–1993). African American contralto. Debuted with New York Philharmonic on August 26, 1925. Friend of Einstein's after he invited her to be a guest in his home when Nassau Inn refused her a room on the occasion of an April 16, 1937, recital in Princeton. Banned from performing in the Daughters of the American Revolution's Constitution Hall in Washington, D.C., in 1939, she instead gave a famous Easter Sunday concert on the steps of the Lincoln Memorial. First African American person to perform with the Metropolitan Opera in New York, January 7, 1955.

John Stewart Bell (1928–1990). British physicist. Proved "Bell's Theorem" (1964), according to which the predictions of local hidden variables theories for certain quantum correlation experiments must satisfy an inequality, "Bell's inequality," which is violated by the predictions of orthodox quantum mechanics. Later experimental tests verified the quantum mechanical predictions. Ph.D. at Birmingham. Worked mainly at CERN—the European Center for Nuclear Physics near Geneva—where he did theoretical particle physics and accelerator design.

Michele Angelo Besso (1873–1955). Swiss engineer. Einstein's closest personal friend from his university days to the end of his life. Einstein's colleague at the Swiss Federal Patent Office (1904–1908). Held various other engineering jobs and then returned to Swiss Patent Office (there from 1920 to 1938). Married Anna Winteler, sister of Einstein's first love, Marie Winteler. Intermediary between Albert and Mileva at the time of their separation and divorce. The only person whom Einstein credits by name for help with the 1905 relativity paper. Later collaborated with Einstein on calculations of advance of Mercury's perihelion according to the early, mistaken, *Entwurf* version of the general theory of relativity.

Hans Bethe (1906–2005). German physicist. Important theoretical contributions to atomic and hydrogen bomb design, though in later life a staunch opponent of work on nuclear weapons and an opponent of the Strategic Defense Initiative. Also important theoretical work on stellar nucleosynthesis, the production of heavier elements in stars. Completed Ph.D. under Arnold Sommerfeld in Munich. Left Germany in 1933; taught physics at Cornell from 1935. Nobel Prize in Physics, 1967.

David Bohm (1917–1992). American physicist. Famous proponent of hidden variables interpretation of quantum mechanics, which he revived in 1952. Codiscoverer of the Aharonov-Bohm effect (1959). Completed Ph.D. under J. Robert Oppenheimer at Berkeley in 1943. Activity in many leftist and communist organizations made a career in the United States impossible during the McCarthy years; contract at Princeton not renewed in 1951. U.S. passport seized while teaching at University of São Paulo, Brazil. Worked briefly in Israel and then (from 1957 on) in Britain, becoming Professor of Theoretical Physics at Birkbeck College London in 1961.

Niels Bohr (1885–1962). Danish physicist. Developed Bohr model of the atom (1913) and complementarity or "Copenhagen" interpretation of quantum mechanics (1927). Involved in nearly 30-year-long dispute with Einstein over the adequacy of quantum mechanics as a framework for fundamental physics; principal target of Einstein-Podolsky-Rosen (EPR) paper. Prominent leader of post–World War II campaign for international control of atomic energy. Nobel Prize in Physics, 1922.

Ludwig Boltzmann (1844–1906). Austrian physicist. Best known for establishing the foundations of modern statistical mechanics, which seeks to explain macroscopic thermal phenomena (such as an isolated system's tendency to maximize its entropy) in terms of the statistics of the motions of the system's myriad atomic and molecular constituents. Introduced the principle linking entropy and probability. Famous proponent of the atomic hypothesis. Taught at Vienna from 1873 to his death. Ernst Mach's successor in the chair for the history and philosophy of inductive sciences at Vienna in 1902. Committed suicide in 1906.

Max Born (1882–1970). German physicist. Taught at Berlin (1915–1919), where he and his wife, Hedwig, formed a life-long friendship with Einstein. Taught briefly at Frankfurt and then from 1921 to 1933 at Göttingen, where he made major contributions to the development of the quantum theory, especially matrix mechanics and the probabilistic interpretation of the quantum mechanical wave function. Taught at Cambridge (1933–1935) and at Edinburgh (1935–1953). Grandfather of Olivia Newton-John. Nobel Prize in Physics, 1954.

Satyendra Nath Bose (1894–1974). Indian physicist. Famous for inventing the derivation of the Planck formula for black-body radiation that became the basis for Bose-Einstein statistics, one of two kinds of nonclassical, quantum statistics of elementary particles. Educated in his native Calcutta, he taught physics in Dacca (now Dhaka, Bangaladesh) from 1921 to 1945 and then back in Calcutta until retirement in 1956.

Walther Bothe (1891–1957). German physicist. Collaborated with colleague Hans Geiger at the Imperial Physical-Technical Institute in Berlin on the Bothe-Geiger experiment (1925), which confirmed strict energy and momentum conservation in electron scattering. Later worked in the 1920s with Einstein on experimental investigations of quantum correlations. After brief professorship in Giessen, took over the Physics Institute at the Kaiser Wilhelm Institute for Medical Research in Heidelberg, which later became the Max-Planck Institute for Nuclear Physics. Nobel Prize in Physics, 1954.

Georges Braque (1882–1963). French Modernist painter. Best known, along with Picasso, for the invention of the movement known as Cubism (1908–1914). The cubist style attempted the simultaneous presentation of multiple perspectives. After recovering from severe wounds suffered during World War I, he returned to Normandy, where he had grown up, and his paintings became somewhat more straightforwardly representationalist.

Gustav Bucky (1880–1963). German American radiologist. Longtime close friend of Einstein's after they met in Berlin in the 1920s. Famous for developing a lead grid that improved the resolution of medical X-rays by absorbing scattered X-rays (c. 1913). Emigrated to New York in 1923, went back to Berlin in 1930 as director of radiology at a Berlin hospital, but returned to New York in 1933, after which time he and Einstein met frequently. Collaborated with Einstein on a 1936 patent for a "light intensity self-adjusting camera."

Rudolf Carnap (1891–1970). German philosopher. Prominent representative of logical empiricism; defender of the verifiability criterion of meaningfulness. Taught at Prague (1931–1935), Chicago (1935–1954), and UCLA (1954–1970).

Ernst Cassirer (1874–1945). German philosopher. Prominent representative of Marburg neo-Kantian school. Important book on neo-Kantian interpretation of relativity (1921), which Einstein respectfully criticized in correspondence. Later famous for *Philosophy of Symbolic Forms*. Taught at Hamburg (1919–1933), and then at Oxford, Gothenburg (Sweden), Yale, and Columbia.

Hermann Cohen (1842–1918). German philosopher. Leading figure in the neo-Kantian movement, representing a position known as "critical idealism," which sought to free Kant's philosophy from dependence on intuition. Also a leading Jewish intellectual, who promoted a rationalist conception of religion. In 1875 he became the first Jew named a professor of philosophy in Germany, at Marburg, where he founded an important tradition of neo-Kantian philosophy that also included Ernst Cassirer and Einstein's teacher, August Stadler.

Marie Curie (1867–1934). Polish-French physicist and chemist. Together with husband Pierre Curie, discovered radium (1898) and other radioactive elements. Met Einstein at 1911 Solvay Congress; took hiking trip with Einstein in Engadine region of Switzerland in 1913. Nobel Prize in Physics, 1903; Nobel Prize in Chemistry, 1911.

Louis de Broglie (1892–1987). French physicist. Proposed extending wave-particle duality to material particles such as electrons (1924). Early proponent of hidden-variable, causal interpretation of quantum theory, which he abandoned until after the revival of the idea by David Bohm in the early 1950s. Nobel Prize in Physics, 1929.

Wander Johannes de Haas (1878–1960). Dutch physicist and mathematician. Trained at Leiden, he taught at Delft, Groningen, and finally (in 1924) Leiden, where he was the successor to his teacher, Heike Kamerlingh Onnes. Married to Hendrik Lorentz's daughter. Famous for work on low-temperature physics. Collaborated with Einstein in the mid-1910s on demonstrating the Einstein-de Haas effect, in which rotation is induced in a magnet by applying a current to a coil surrounding the magnet.

Willem de Sitter (1872–1934). Dutch mathematician, physicist, and astronomer. Taught at Leiden University and director of the Leiden Observatory. Discovered the first exact cosmological solution of the Einstein field equations (1917), which entailed the possibility of a non-static universe. Einstein introduced the infamous cosmological constant to block such non-static solutions of the field equations.

W. E. B. Du Bois (1868–1963). African American civil rights leader, historian, sociologist, educator, and writer. After earning a Ph.D. from Harvard and studying at the University of Berlin, he taught at Wilberforce University, the University of Pennsylvania, and what is now Clark Atlanta University. Starting in 1910 he edited *The Crisis*, the official magazine of the National Association for the Advancement of Colored People. In 1934 he returned to Clark Atlanta University feeling that the NAACP had become too conservative.

Pierre Duhem (1861–1916). French physical chemist, historian of science, and philosopher of science. His *Aim and Structure of Physical Theory* (1906), which argued for theory holism and the underdetermination of theory choice by evidence, was a major influence on Einstein's philosophy of science. Taught at Lille, Rennes, and Bordeaux. Elected to membership in the Académie des Sciences in 1913.

Helen Dukas (1896–1982). Einstein's secretary. Born and raised in Freiburg; her mother was from Hechingen, the hometown of Einstein's second wife, Elsa Löwenthal, through which connection she secured the position as Einstein's secretary in 1928. After Elsa Einstein's death in 1936, Dukas took over the running of Einstein's household in Princeton. Co-trustee of Einstein's literary estate with Otto Nathan. Coauthored the biography *Albert Einstein: Creator and Rebel* with Bannesh Hoffmann.

Lawrence Durrell (1912–1990). English novelist and travel writer. Born in India, educated in England; lived and worked on the island of Corfu before World War II, then in Alexandria and Cairo, Egypt, during the war. After the war, his life as a teacher and diplomat took him to many parts of the world. His most famous work is the *Alexandria Quartet*, a sequence of four novels set in Alexandria—*Justine* (1957), *Balthazar* (1958), *Mountolive* (1958), and *Clea* (1960)—and supposed to exemplify the idea of three different spatial and one temporal perspective on the same set of events, in an explicit allusion to Einstein and relativity.

Arthur Eddington (1882–1944). English astronomer and cosmologist. Leader of the 1919 eclipse expedition that confirmed Einstein's prediction from general relativity of the bending of light near the Sun. Taught at Cambridge, director of Cambridge Observatory, and member of the Royal Society.

Thomas Edison (1847–1931). American inventor. The "Wizard of Menlo Park" (location of his research laboratory in New Jersey), Edison was famous for many inventions, ranging from the carbon filament, incandescent electric light bulb and the phonograph to the Kinetoscope and the Vitascope for viewing motion pictures.

Paul Ehrenfest (1880–1933). Austrian physicist. Important contributions to statistical mechanics, relativity, and quantum theory. One of Einstein's closest personal friends within the physics community. Successor of H. A. Lorentz at Leiden (1912–1933), for which position he was strongly recommended by Einstein. Committed suicide, partly due to depression over his worry that his ability to do physics was in decline.

Eduard Einstein (1910–1965). Second son of Einstein and first wife, Mileva. Known affectionately as "Tete." Early signs of academic and musical talent were eclipsed by steadily worsening mental problems, diagnosed as schizophrenia, starting around the age of 20. Institutionalized for much of his later life. After his mother's death in 1948, he was looked after by Einstein's Swiss biographer, Carl Seelig.

Hans Albert Einstein (1904–1973). Swiss American engineer. First son of Einstein and first wife, Mileva. Trained at the ETH in Zurich. Married Frieda Knecht in 1927. Three children: Bernhard Caesar Einstein (b. 1930), Klaus Martin Einstein (1932–1938), and adopted daughter Eveyln Einstein (b. 1941). After first wife's death in 1958, he married Elizabeth Roboz. Worked as a steel engineer in Dortmund, Germany, for 10 years before emigrating with his family to the United States in 1938. Employed for a while at an agricultural experiment station in South Carolina, then took a position at Caltech, and later went to the University of California, Berkeley, as a professor of hydraulic engineering in 1947.

Hermann Einstein (1847–1902). Einstein's father. Born in Buchau, Württemberg, to Abraham Einstein and Helene Moos. Secondary school in Stuttgart. Joined his cousins' feather-bed business in Ulm shortly after marriage to Pauline Koch in 1876. With brother Jakob, started an electrotechnical firm, Einstein & Cie, in Munich in 1880. Business failures led to the firm's relocation to northern Italy in 1894. Continuing business problems left the family comparatively poor at the time of Hermann's death from heart failure in 1902.

Ilse Einstein (1897–1934). Einstein's stepdaughter, biological daughter of Max and Elsa Löwenthal. Einstein's secretary at the Kaiser Wilhelm Institute for Physics in the late 1910s and early 1920s. Married writer Rudolf Kayser in 1924, who published a noteworthy biography of Einstein in 1930, a biography warmly regarded by Einstein himself. Kayser also managed to get Einstein's papers out of Berlin after the Nazi seizure of power in 1933. Ilse died in Paris in 1934.

Jakob Einstein (1850–1912). Einstein's uncle; brother and business partner of Einstein's father, Hermann. Born in Buchau, Württemberg. Co-owner with Hermann Einstein of the Einstein & Cie electrotechnical firm in Munich and later in northern Italy. Married Ida Einstein in 1882. Two children: Robert Einstein (1884) and Edith Einstein (1888); divorced in 1909. After the collapse of the brothers' firm he eventually found employment as director of an electrical firm in Vienna, where he died in 1912.

Maja Einstein (1881–1951). Einstein's sister. Trained first as a teacher of romance languages. Earned Ph.D. in French Literature, University of Bern, 1909. Married Paul Winteler, son of Jost Winteler and brother of Einstein's first love, Marie Winteler, in 1911. Lived in Lucerne, Switzerland, and later near Florence, Italy. Emigrated alone to the United States in 1939, where she lived with her brother in Princeton until her death.

Margot Einstein (1899–1986). Einstein's stepdaughter, biological daughter of Max and Elsa Löwenthal. Sculptor. Married Dmitri Marianoff, a Soviet journalist then directing the cinema division of the Soviet trade mission in Berlin in 1930. Accompanied Marianoff guiding Rabindranath Tagore on a tour of the Soviet Union. Separated from Marianoff in 1934, when she accompanied her mother back to the United States following the death of sister, Ilse. Divorced in 1937. Lived with stepfather Einstein in Princeton. In 1944, Marianoff published a biography of Einstein that Einstein publicly repudiated as "generally unreliable."

Pauline Einstein (1858–1920). Einstein's mother. Born Pauline Koch in Canstatt, Württemberg. Daughter of a grain merchant, Julius Koch. Married Hermann Einstein in 1876. After husband's death in 1903, poverty consequent upon the failure of the family's electrotechnical business forced her to move from Italy back to Württemberg, where she supported herself with work as a housekeeper and lived with her sister Fanny and brother-in-law Rudolf Einstein (parents of Albert's second wife, Elsa Löwenthal). Moved with them to Berlin in 1911 and later lived for a time in Berlin with her brother. Living with Albert and his second wife, Elsa, in Berlin at the time of her death from abdominal cancer in 1920.

Lieserl Einstein-Marić (1902–unknown). Illegitimate daughter of Einstein and Mileva Marić, born at Marić's parents' home in Novi Sad, Serbia, then a part of Hungary. Survived an early bout of scarlet fever. After that, all record of her existence disappears.

James Franck (1882–1964). German American physicist. Ph.D. at Berlin, where he taught until 1918. Taught at Göttingen from 1920 to 1933, where he directed the Second Physical Institute. Famous for the Franck-Hertz experiment (1914), which confirmed Bohr's predication that orbital electrons absorb electromagnetic energy only in discrete quantum units. Emigrated to the United States in 1933, settling eventually at the University of Chicago, where he was a leading figure in the Manhattan Project. In the summer of 1945 he spearheaded the preparation of the "Franck Report," which urged that the atom bomb not be used in a surprise attack against Japanese civilians. Nobel Prize for Physics, 1925.

Philipp Frank (1884–1966). Austrian physicist and philosopher of science. Einstein's successor in the physics chair at the German university in Prague in 1912. Major figure in the logical empiricist movement in the philosophy of science. Emigrated to the United States in 1938 and taught at Harvard, from where (after 1945) he assumed the leadership of the remaining institutional structure of the Vienna Circle. Defended Einstein against charges that physical relativity implied relativity in morals. Also one of Einstein's first biographers.

William Frauenglass (1905–1998). American schoolteacher. Subpoenaed to testify before the Senate Internal Security Subcommittee in 1953, he sought Einstein's advice on how to respond. Einstein's letter advising Frauenglass to refuse to cooperate was published in *The New York Times* and became a source of inspiration and encouragement to other targets of persecution during the McCarthy period.

Erwin Finlay Freundlich (1885–1964). German astronomer and astrophysicist. Led the first expedition in 1914 to test Einstein's prediction of the bending of light near the Sun during an eclipse; expedition was unsuccessful due to his being interned by the Russians at the outbreak of World War I. After the war, he oversaw the design and construction and then directed the operations of the "Einstein Tower," a solar observatory in Potsdam built to test general relativity—also a masterpiece of Modernist architecture by the architect Erich Mendelsohn. Emigrated to Istanbul, Turkey, in 1933 and worked for many years at St. Andrews in Scotland.

Alexander Friedman (1888–1925). Russian cosmologist and mathematician. Discovered expanding universe solution to Einstein's gravitational field equations (1922), later confirmed by the work of Edwin Hubble.

Galileo Galilei (1564–1642). Italian physicist, astronomer, mathematician, and philosopher. Best known for his defense of the Copernican heliocentric model of the planetary system, for which he provided compelling empirical evidence with his original telescopic observations. Famous also for helping to establish the foundations of the modern science of mechanics. Condemned by the Inquisition in 1633 for his defense of Copernicanism and sentenced to house arrest at his home outside Florence.

Kurt Gödel (1906–1978). Austrian logician and mathematician. Proved the incompleteness of arithmetic (1931). Discovered solutions of Einstein field equations for general relativity incorporating closed, time-like trajectories (1949). Einstein's friend and colleague at the Institute for Advanced Study in Princeton (1940–1955).

Clement Greenberg (1909–1994). American art critic. Influential theorist of Modernism in art and promoter of abstract expressionist painters such as Jackson Pollock. Longtime art critic for *The Nation*. Defined Modernism in terms of the painting's reflexive self-criticism of its own production and its being a critical commentary on experience.

Marcel Grossmann (1878–1936). Swiss mathematician. Einstein's ETH classmate and friend. Collaborated with Einstein on early version of general theory of relativity. Father arranged Einstein's appointment to Swiss Federal Patent Office in 1902. Taught mathematics at the ETH from 1907 to 1927, where he was Einstein's colleague from 1912 to 1914.

Fritz Haber (1868–1934). German chemist. Developed Haber process for synthesizing ammonia from hydrogen and atmospheric nitrogen. Developed poison gas weapons in World War I. Played central role in recruiting Einstein to Berlin in 1914. Dismissed by Nazis in 1933. Nobel Prize in Chemistry, 1918.

Conrad Habicht (1876–1958). Swiss physics and mathematics teacher. Lifelong friend of Einstein's after meeting in Habicht's native Schaffhausen, Switzerland, when Einstein taught there briefly in 1901 at a private boys' school. Member of the Olympia Academy in Bern. Collaborated with Einstein and brother Paul Habicht on the *Maschinchen*, the device for amplifying and measuring small electrical potentials. Taught for many years in the Cantonal School in Schaffhausen.

Paul Habicht (1884–1948). Swiss machinist and electrical engineer. Younger brother of Conrad Habicht. Collaborated on the design and manufacture of the *Maschinchen.* In later years ran his own electrotechnical firm in his native Schaffhausen, Switzerland, but the company experienced only limited success.

Otto Hahn (1879–1968). German chemist. Together with longtime collaborator Lise Meitner and assistant Fritz Strassmann, discovered nuclear fission (1938). Worked at Kaiser Wilhelm Institute for Chemistry in Berlin-Dahlem, which he directed from 1928 to 1946. Nobel Prize in Chemistry, 1944.

Werner Heisenberg (1901–1976). German physicist. Inventor of matrix mechanical formalism for quantum mechanics (1925). Discovered quantum indeterminacy/uncertainty principle (1927). Completed Ph.D. under Arnold Sommerfeld in Munich. Assistant to Max Born in Göttingen, 1923; worked with Niels Bohr in Copenhagen, 1924–1925. Professor at Leipzig, 1927–1941. Director of German atomic bomb project during World War II. Nobel Prize in Physics, 1932.

Theodor Herzl (1860–1904). Austro-Hungarian journalist. Founder of the Zionist movement (1897), which promoted the creation of a Jewish homeland and state in Palestine.

David Hilbert (1862–1943). German mathematician. Developed and promoted the formalist program in the foundations of mathematics. Leader of the mathematical community in Göttingen, which was noted for its emphasis on relations between mathematics and the natural sciences. Discovered general theory of relativity simultaneously with, but independently of, Einstein (1915).

J. Edgar Hoover (1895–1972). American lawyer. Longtime director of the Federal Bureau of Investigation (1924–1972). Achieved early fame for attacks on organized crime, but later criticized widely for using the FBI as a tool for political persecution of leftists and civil rights activists. He was a legendary power in Washington, and several presidents upset by his methods and influence dared not fire him out of fear of the repercussions.

Edwin Hubble (1889–1953). American astronomer. First discovered the existence of galaxies beyond the Milky Way (1925). Also discovered that the red shift of galaxies is proportional to their distance (1929), thus proving that the universe is expanding, which led to Einstein's removing the cosmological constant from the gravitational field equations of general relativity. Worked at the Mount Wilson Observatory in Pasadena, California (1919–1953).

David Hume (1711–1776). Scottish philosopher. Prominent representative of empiricism, the view that knowledge is grounded in experience, defended in works like the *Treatise of Human Nature* (1739–1740). Einstein credited Hume's philosophy with having stimulated the key insight about the nature of time that was crucial in the breakthrough to the special theory of relativity.

Immanuel Kant (1724–1804). German philosopher. Probably the single most influential philosopher since the time of Socrates, Plato, and Aristotle, his philosophy is known as critical idealism. Famous for arguing that space and time are necessary a priori structures of experience and that causality and other categories are necessary a priori structures of cognition, all of which claims were challenged by the new physics of the 20th century. An important influence on Einstein, who read all of Kant's major works around the age of 12 or 13, later studied Kant at university, but eventually repudiated the central tenets of Kant's philosophy under the influence of empiricists like Ernst Mach and conventionalists like Henri Poincaré and Pierre Duhem. Lived his entire life in his native Königsberg, where he also had his university appointment.

Alfred Kleiner (1849–1916). Swiss physicist. Director of Einstein's doctoral dissertation at the University of Zurich in 1905, later Einstein's colleague in physics at the University of Zurich (1909–1911), where he was director of the physics institute and played a leading role in organizing the offer of an academic position to Einstein. Worked mainly on electrical measurement devices.

Édouard Le Roy (1870–1954). French mathematical physicist and philosopher. Defender of a radical form of conventionalism that denied the existence of a "universal invariant" common among alternative, empirically equivalent theories, a view famously criticized by Poincaré. A prominent representative of a Modernist Catholic philosophical position defending the moral value of dogma despite its possible incompatibility with scientific rationality. Henri Bergson's successor at the Collège de France in 1921.

Georges Lemaître (1894–1966). Belgian priest, physicist, and astronomer. Important work on cosmological solutions of Einstein's gravitational field equations of general relativity; early proponent of the idea that the universe was expanding (1927). Taught at Catholic University of Louvain. Member (1936) and President (1960–1966) of Pontifical Academy of Sciences.

Philipp Lenard (1862–1947). German experimental physicist. Trained at Heidelberg, where, after several appointments elsewhere, he taught for many years from 1907. Famous for experimental work on the photoelectric effect demonstrating that the energy of the electrons emitted from an illuminated metallic surface was independent of the intensity of the light and proportional to its frequency. Later became a prominent figure in the anti-relativity "German physics" movement, as part of which he had a famous showdown with Einstein at the 1920 annual meeting of German natural scientists and physicians. Nobel Prize for Physics, 1905.

Hendrik Antoon Lorentz (1853–1928). Dutch physicist. Important contributions to electrodynamics and champion of the electron theory, which postulated the fundamentally electrical nature of all physical substance. Proposed "Lorentz contraction," the literal, physical shortening of objects in the direction of their hypothetical motion through the ether, in order to explain the null result of the Michelson-Morely experiment. Highly regarded by Einstein, who nevertheless declined an offer to be Lorentz's successor in Leiden, where Lorentz taught from 1878 to his retirement in 1912. Nobel Prize for Physics, 1902.

Elsa Löwenthal (1876–1936). Einstein's cousin and second wife. Born in Hechingen, Württemberg, to textile manufacturer Rudolf Einstein (first cousin of Albert's father, Hermann Einstein) and Fanny Koch (older sister of Einstein's mother, Pauline Koch). Rudolf Einstein was also the major creditor of the Einstein brothers' electrotechnical firm in Munich and in Italy. Elsa married Max Löwenthal (from Berlin), co-owner of a textile firm in Hechingen, in 1896. Three children: Ilse, 1897; Margot, 1899; and a son in 1903 who died the same year. Divorced in 1908 and moved in with her parents, now also living in Berlin, along with her two daughters. Began an affair with Albert in 1912 and married him in 1919, shortly after his divorce from Mileva was finalized. Emigrated to the United States with Albert in 1933. Died in Princeton from heart and kidney disease.

Trofim Lysenko (1898–1976). Russian biologist and agronomist. For many years, head of the Academy of Agricultural Sciences and director of the Institute of Genetics in the Soviet Academy of Sciences. A defender of the Lamarckian theory of the inheritance of acquired characteristics, Lysenko led a campaign of repression in the Soviet Union against Darwinian biology and Mendelian genetics, setting back for many decades the development of the biological sciences in the Soviet Union.

Ernst Mach (1838–1916). Austrian physicist, historian of science, and philosopher of science. Leading representative of positivism and a precursor of logical empiricism. Young Einstein read and was deeply influenced by many of his books; Einstein acknowledged Mach as an important influence in the genesis of special relativity. Taught at Graz, Prague, and Vienna, where he occupied the chair in history and philosophy of inductive sciences (1895–1901).

Gustav Maier (1844–1923). German banker and political activist. A longtime friend to Einstein's father and mentor to the young Einstein. Directed banks in Ulm, Frankfurt, and Zurich. Arranged Einstein's ETH entrance examination in 1895 and Einstein's living with Jost Winteler in Aarau. Cofounder of the Frankfurt Peace Union and the Swiss Ethical Culture Society; later active in the Zurich Peace Union. Well known as a writer on social and economic issues, his 1898 book on social movements and theories went through nine editions.

Mileva Marić (1875–1948). Born and raised in Serbia, the daughter of a civil servant in the Hungarian government. Received extraordinary permission to study at an all-male gymnasium in Zagreb. Studied medicine at the University of Zurich, then physics at the ETH, where she and Einstein met. Twice failed her final degree examination at the ETH. Gave birth to Einstein's illegitimate daughter, Lieserl, in 1902. Married Einstein in 1904. Two sons: Hans Albert, 1904; Eduard, 1910. Separated from Einstein in 1914 and divorced in 1919. Received Einstein's Nobel Prize money in 1922 and later lived off of income from properties that Einstein purchased for her in Zurich.

James Clerk Maxwell (1831–1879). Scottish physicist. Famous for giving an elegant mathematical formulation of classical electrodynamics, unifying electricity and magnetism, demonstrating the wavelike propagation of electromagnetic energy, and proving that light is a form of electromagnetic radiation. Important work also on thermodynamics and kinetic theory of heat. Taught at Aberdeen, King's College London, and Cambridge.

Lise Meitner (1878–1968). Austrian physicist. Longtime collaborator with Otto Hahn at the Kaiser Wilhelm Institute of Chemistry in Berlin-Dahlem. Codiscover, with Hahn, of nuclear fission (1938). Fled to Sweden in 1938; moved to Britain in 1960.

Albert Michelson (1852–1931). American physicist. Carried out the famous Michelson-Morely experiment (1887), in which an interferometer failed to detect the expected effects of the Earth's motion through the hypothetical electromagnetic ether, an experiment that became part of the background to Einstein's special theory of relativity. Taught at Case School of Applied Science in Cleveland, Clark University, and the University of Chicago. Nobel Prize in Physics, 1907.

Robert Millikan (1868–1953). American experimental physicist. Famous for the determination of the charge of the electron and for confirmation of crucial implications of Einstein's theory of the photoelectric effect. Taught for many years at the University of Chicago and then served from 1921 to 1945 as president of the new California Institute of Technology, which he rapidly built into one of the world's preeminent technical universities. Recruited Einstein to a regular part-time visiting appointment at Caltech in the early 1930s. Nobel Prize for Physics, 1923.

Hermann Minkowski (1864–1909). Lithuanian-German mathematician. One of Einstein's mathematics teachers at the ETH; later a prominent member of the mathematics faculty at Göttingen, where he was a colleague of David Hilbert. Invented the modern geometrical representation of relativistic space-time on a 4-dimensional point manifold (1907). Somewhat surprised by the achievements of Einstein, whom he remembered as not a very distinguished student in mathematics.

Claude Monet (1840–1926). French Modernist painter. Best known as the founder of the impressionist movement, so named after the exhibition of Monet's painting, *Impression, Sunrise* in 1874. After extensive travels in his early years, Monet worked from 1883 until his death mainly at his home in Giverny. Especially in these later years, he focused on producing the many series of paintings (such as the *Haystacks* series) for which he is famous: series illustrating the same subject in many different contexts.

Eadweard Muybridge (1830–1904). English photographer. Important early work on using multiple coordinated cameras to analyze continuous motions into sequences of still photographs, a technique useful for understanding such human and animal motion. Worked in the United States for most of the period between 1855 and 1894, at first mainly in San Francisco, later at the University of Pennsylvania. Returned to England in 1894.

Otto Nathan (1893–1987). German American economist. Close personal friend to Einstein and co-trustee of Einstein's literary estate with Einstein's secretary, Helen Dukas. An expert on the German economic system under the Nazis, Nathan had been an economic advisor to the German government during the Weimar period of the 1920s to early 1930s. After emigrating to the United States in 1933, he taught at Princeton, NYU, Vassar, and Howard University. Coeditor with Heinz Norden of the collection *Einstein on Peace*.

Walther Nernst (1864–1941). German physicist. One of the founders of modern physical chemistry. Enunciated the third law of thermodynamics (1905), which asserts that the entropy of a substance approaches zero as the temperature approaches absolute zero, thus establishing an absolute entropy scale. Central role in recruiting Einstein to Berlin in 1914. Taught at the University of Berlin (1905–1932). Nobel Prize in Chemistry, 1920.

Isaac Newton (1643–1727). English natural philosopher, mathematician, and astronomer. Established the science of classical mechanics with his 1687 *Mathematical Principles of Natural Philosophy*. Co-inventor of the calculus. Important work on optics. Inventor of the refracting telescope. Extensive writings on theology representing an anti-Trinitarian point of view. Graduated from Trinity College, Cambridge, and elected Lucasian Professor of Mathematics at Cambridge in 1669. Moved to London as Warden (1696) and later Master (1711) of the Royal Mint. Resigned from Cambridge in 1701. President of the Royal Society from 1703 until his death.

Julius Nieuwland (1878–1936). Belgian American priest and chemist. Emigrated with his parents to South Bend, Indiana, in 1880. Studied at Notre Dame, ordained a priest in the Holy Cross order in 1903. Ph.D. in Chemistry at Catholic University in 1904. Discovered the chemical processes that are the basis for making synthetic rubber (neoprene) and the acetylene derivative, lewisite, which was developed for use as a poison weapon. Taught botany and chemistry for many years at Notre Dame. Failed to persuade Knute Rocke to become a chemist rather than a football coach. Awarded the Nichols medal by the American Chemical Society, 1935.

J. Robert Oppenheimer (1904–1967). American physicist. Director of the Manhattan Project, which developed the atomic bomb. Taught at Caltech and Berkeley. Director of Institute for Advanced Study (1947–1967), where he was Einstein's boss. In a famous case of political persecution, deprived of security clearance in 1953 in part because of his skepticism about the wisdom of developing the hydrogen bomb.

Wolfgang Pauli (1900–1958). Austrian physicist. Proposed idea of electron "spin" and Pauli exclusion principle (1924), which states that no two electrons can exist in exactly the same state, including spin. Studied under Arnold Sommerfeld in Munich (1918–1921). Assistant to Max Born in Göttingen, lecturer in Hamburg (1923–1928), professor at ETH in Zurich after 1928. Nobel Prize in Physics, 1945.

Pablo Picasso (1881–1973). Spanish Modernist painter and sculptor. Highly inventive and never long to continue any one style, he is famous, along with Georges Braque, for the development of Cubism between 1908 and 1919. Also played an important role in the development of Surrealism and neo-Expressionism. Active mainly in Paris from 1904 through the 1950s, but also in Barcelona in the earlier part of this period. Lived and worked mainly in the south of France in later years.

Max Planck (1858–1947). German physicist. Important early work on thermodynamics and statistical physics. Discovered energy quantization in 1900. A teacher of many top physicists and an influential figure in the politics and institutional structures of German physics. Einstein's colleague in University of Berlin physics department (1914–1933; emeritus after 1926). Tried in vain to oppose Hitler's expulsion of Jewish scientists in 1933. Nobel Prize in Physics, 1918.

Henri Poincaré (1854–1912). French physicist, mathematician, and philosopher of science. Anticipated several ideas central to Einstein's theory of special relativity. Developed the concept of classical chaos. Proponent of conventionalism in philosophy of science. A major philosophical influence on Einstein, who read some of Poincaré's writings in the Olympia Academy. Lectured for many years at the Sorbonne. A member of the Académie des sciences (from 1887) and the Académie française (from 1909).

Walther Rathenau (1867–1922). German industrialist and statesman. Son of Emil Rathenau, founder of the German Allgemeine Elektrizitäts Gesellschaft (AEG—the German General Electric Corporation), he later became head of that firm. Good friend of Einstein's. Served in the Raw Materials Department of the German Ministry of War during World War I. A leading member of the liberal German Democratic Party, in 1921 he was appointed Minister of Reconstruction for the new Weimar government, and in 1922, foreign minister. Assassinated by people associated with an extreme right-wing group in June 1922.

Hans Reichenbach (1891–1953). German philosopher. Student of Einstein's, Berlin, late 1910s. Einstein's colleague in University of Berlin physics department (1926–1933). Leading representative of logical empiricism/scientific philosophy in Germany; wrote important books on philosophy of relativity theory. Emigrated to Turkey in 1933; settled in United States in 1938, at UCLA.

Emery Reves/Imre Revesz (1904–1981). Hungarian journalist and publisher. Prominent advocate of world government. His book, *The Anatomy of Peace* (1945), was strongly promoted by Einstein as offering a much needed formula for an effective form of world government requiring the renunciation of individual, national sovereignty and the provision to a world government of sufficient military power to enforce its laws and rulings.

Paul Robeson (1898–1976). African American actor, singer, athlete, and civil rights leader. Born in Princeton, New Jersey. A Phi Beta Kappa graduate and valedictorian at Rutgers University, where he also lettered in multiple sports and was named an All-American football player in 1917 and 1918. Earned a law degree from Columbia in 1923, while also playing professional football. A successful Broadway career began in 1924 when he starred in Eugene O'Neill's *Emperor Jones*. Later famous for role of Othello in Shakespeare's play. Prominent in campaigns for civil rights and a vocal leftist, Robeson was the target of multiple investigations in the 1950s because of loyalty concerns. His U.S. passport was revoked in 1950 but restored in 1958 when the Supreme Court ruled in *Kent v. Dulles* that a passport could not be denied on the basis of political beliefs.

Bertrand Russell (1872–1970). British philosopher, logician, mathematician, social reformer, and pacifist. Most important among many influential contributions to philosophy was his work on the foundations of mathematics, epitomized by his *Principia Mathematica* (1910–1913), coauthored with Alfred North Whitehead, which sought to derive all of mathematics from logical first principles. A lifelong pacifist, he was jailed for refusing military service during World War I. Coauthor of the Russell-Einstein Manifesto (1955) opposing the nuclear arms race. Nobel Prize for Literature, 1950.

Andrei Sakharov (1921–1989). Russian nuclear physicist and human rights campaigner. The "father" of the Soviet hydrogen bomb, Sakharov also did important work on power generation from nuclear fusion and later worked in particle physics and cosmology. Became a political activist in the 1960s, first with his opposition to anti-ballistic missile defense systems and later with a broader range of human rights issues. Arrested and sent into internal exile in 1980, he was allowed to return to Moscow only in 1986 after Mikhail Gorbachev began his program of reform. Nobel Prize for Peace, 1975.

Moritz Schlick (1882–1936). German philosopher. Leading member of the Vienna Circle of logical empiricists. Important early writings on philosophical implications of relativity. Completed his Physics Ph.D. under Max Planck in Berlin (1904). Taught philosophy at Rostock (1910–1921) and Kiel (1921–1922) before assuming Ernst Mach's old chair at the University of Vienna in 1922. Assassinated in Vienna in 1936 by a deranged former student who after 1938 was paroled and embraced by Austrian Nazis.

Arthur Schopenhauer (1788–1860). German philosopher. One of the most influential and widely read philosophers of the 19th century. Important critical reaction to Kant relating his philosophy to the Indian Vedantic tradition, which Schopenhauer did much to popularize in Europe. Educated at Göttingen, he started as a lecturer at the University of Berlin but did not pursue an academic career after Hegel proved the more popular lecturer in Berlin. Lived the last 27 years of his life in Frankfurt. His most important book, *The World as Will and Representation* (1819), and many more popular writings made him a voice for alienated young intellectuals, including such figures as Nietzsche, Wittgenstein, and Freud. Significant philosophical influence on Einstein.

Erwin Schrödinger (1887–1961). Austrian physicist. Inventor of wave mechanical formalism for quantum mechanics (1926). Studied in Vienna. Professor at University of Zurich (1922–1927); Einstein's colleague in University of Berlin physics department (1927–1933); at Dublin Institute for Advanced Studies (1940–1955). Nobel Prize in Physics, 1933.

Karl Schwarzschild (1873–1916). German physicist and astronomer. Found the first exact solution to Einstein's gravitational field equations in 1916, providing the physical basis for understanding what eventually came to be known as black holes. Began his career at Göttingen, but became Director of the Potsdam Observatory (outside of Berlin) in 1909 and a member of the Prussian Academy of Sciences in 1912. Died while serving as an artillery officer on the Russian front in the spring of 1916.

Georges Seurat (1859–1891). French Modernist painter. Famous for the employment of the technique of pointillism, which builds up a seemingly continuous image from many individually applied, tiny dots of pigment, exemplified in his masterpiece, *Grand Jatte*. Born and active mainly in Paris. Cofounder of the Société des Artistes Indépendants, which stood opposed to the Paris Salon, the official annual exhibition of the Académie des Beaux-Arts.

Maurice Solovine (1875–1958). Romanian-French editor and publisher. Lifelong friend of Einstein's after signing up for private lessons with him in Bern and then joining the Olympia Academy. Lived and worked in Paris from 1906 to his death. Edited the scholarly journal *Revue Philosophique* (1908–1919). Translated into French and published several Einstein titles, including Einstein's popular book on relativity, his Princeton lectures, *The Meaning of Relativity*, and the Einstein and Infeld history *The Evolution of Physics*. Also published his own correspondence with Einstein.

Baruch Spinoza (1632–1677). Jewish Dutch philosopher. Prominent representative of rationalism, the view that all knowledge is based on self-evident first principles. Defended a strong form of monism, according to which mind and matter are both just modes of one substance that is God or Nature. Also defended a strong form of determinism. Excommunicated by the Amsterdam Jewish community in 1656. Later lived in various locations in the Netherlands, earning a living as a lens grinder. Strong philosophical influence on Einstein.

August Stadler (1850–1910). Swiss philosopher. Einstein's philosophy teacher at the ETH. A student of the eminent Marburg neo-Kantian philosopher Hermann Cohen, Stadler's doctorate was awarded by the University of Zurich in 1874. After two years of study in England, he returned and began a long career teaching philosophy at the ETH in Zurich. Himself a prominent voice in the Marburg or "critical idealist" neo-Kantian tradition, Stadler's 1883 *Kants Theorie der Materie* (Kant's theory of matter) was perhaps his most important work.

Johannes Stark (1874–1957). German experimental physicist. Educated at Munich; taught at Munich, Göttingen, Hanover, Aachen, and Greifswald. Famous for discovering the "Stark effect," the splitting of spectral lines in electrical fields. One of the first prominent physicists to appreciate the significance of Einstein's work in 1905, but later became a leading representative of the anti-relativity "German physics" movement. Nobel Prize for Physics, 1919.

Leo Szilard (1898–1964). Hungarian physicist. Important theoretical work in statistical physics, nuclear physics, and other areas. Together with Einstein, invented a refrigerator in the late 1920s. First to conceive the idea of a nuclear chain reaction, which he patented in 1934. Drafted and secured Einstein's signature on the letter to President Roosevelt in 1939 that led to the creation of the Manhattan Project and the atomic bomb. Later a vigorous campaigner for control of nuclear weapons. Led a kind of peripatetic professional life, mostly without permanent or regular academic appointments.

Max Talmey/Talmud (1867–1941). Polish-Lithuanian ophthalmologist. While a medical student in Munich, was a regular visitor to the Einstein home, where he introduced the young Einstein to popular scientific writings and the works of the philosopher Immanuel Kant. Later a prominent ophthalmologist in New York, Talmey also played an important role in the movement to make Esperanto an international language.

Edward Teller (1908–2003). Hungarian American physicist. The "father of the hydrogen bomb," Teller was a specialist in nuclear physics and prominent promoter of the concept of a fusion bomb even in the early 1940s, when he was working at Los Alamos. Later earned the enmity of many physicists for his role in the events leading to the revocation of J. Robert Oppenheimer's security clearance in 1954. Still controversial late in life, as with his promotion of President Reagan's "Star Wars" Strategic Defense Initiative in the 1980s.

Heinrich Friedrich Weber (1843–1912). German-Swiss physicist. Trained in physics at the University of Jena. Worked in Heidelberg and Karlsruhe, and later in Hohenheim. Hermann von Helmholtz's first physics assistant at the University of Berlin. Longtime professor of physics at the ETH in Zurich, where he was Einstein's physics teacher. An expert on the physics of precision measurements, he directed at the ETH a state-of-the-art laboratory funded by the German industrialist Werner von Siemens.

Chaim Weizmann (1874–1952). Russian-British chemist and Zionist leader. Famous for developing a process to produce acetone through bacterial fermentation. Taught at Geneva and Manchester. Became a British subject in 1910, and while earning notice for the direction of wartime scientific research he became an unofficial advisor to the British government on Jewish issues in Palestine because he also had become a prominent Zionist. Played a major role in crafting the Balfour Declaration, which committed Britain to establishing a Jewish national home in Palestine. First president of Israel, 1949.

Hermann Weyl (1885–1955). German mathematician. Important contributions to the foundations of mathematics, topology, group theory, physics, and the philosophy of science. Invented the first unified field theory uniting electromagnetism and Einstein's theory of gravitation (1918), in which context he also invented the modern notion of gauge freedom in mathematical physics. His philosophy of science was heavily influenced by the phenomenology of Edmund Husserl. A student of David Hilbert's at Göttingen, he taught for many years at the ETH in Zurich, then briefly worked as Hilbert's successor in Göttingen before leaving Germany in 1933 and settling in a job at the Institute for Advanced Study in Princeton.

Jost Winteler (1846–1929). Swiss educator. Trained in history at the University of Zurich and in philology at the University of Jena. Longtime teacher of Greek and history at the Aargau Cantonal School, which Einstein attended (1895–1896) while rooming in the Winteler home. Daughter Marie was Einstein's first love. Daughter Anna married Einstein's best friend, Michele Besso, and son Paul married Einstein's sister, Maja.

Marie Winteler (1877–1957). Daughter of Jost Winteler and Einstein's first love (c. 1896–1897). Trained as a teacher and governess. Married Albert Müller, a watch factory manager in Büren, Canton of Bern, Switzerland, by whom she had two children. Gave private music lessons for many years. Divorced in 1927. Lived in Zurich from 1938 to around 1950; thereafter in Meiringen, Canton of Bern.

Stephen S. Wise (1874–1949). Hungarian American rabbi. A leading figure in the Reform Judaism movement in the United States, Wise was also an early and energetic supporter of the Zionist movement. Prominently identified with a variety of progressive social causes. A personal friend to both President Franklin Roosevelt and Einstein.

Xu Liangying (b. 1920). Chinese physicist, historian of science, and human rights campaigner. Translator for the three-volume edition of Einstein's collected works in Chinese, a publication that played a surprisingly important role in the democratization movement in China starting in the late 1970s. Xu was sentenced to internal exile as a "rightist" from 1957 to 1978, when he was allowed to resume his position in the Chinese Academy of Sciences. Winner of the Sakharov Prize from the American Physical Society in 2008.

Bibliography

A Note about Einstein Biographies

The reader interested in learning more about Einstein is confronted by a bewildering array of biographies. For the purpose of these lectures, I suggest as a source of basic information the 2007 biography by Walter Isaacson, *Einstein: His Life and Universe*. It's the best of the recent crop of comprehensive biographies (though I caution that Isaacson cannot always be trusted on the science or the philosophy). For more specific purposes, I also recommend the biographies by Thomas Levenson, *Einstein in Berlin* (2003); Arthur Miller, *Einstein, Picasso: Space, Time, and the Beauty That Causes Havoc* (2001); Dennis Overbye, *Einstein in Love: A Scientific Romance* (2000); and Abraham Pais, *"Subtle is the Lord …": The Science and the Life of Albert Einstein* (1982).

One challenge facing any Einstein biographer is having to be master not just of the art of writing, of history, and of the details of Einstein's life, but also of technical physics and philosophy. Another challenge is that important new documentary material is being discovered all the time, so any biography is quickly somewhat out of date. These challenges notwithstanding, there are other biographies, both old and new, that can be read with profit. Among the recent comprehensive biographies, at least three are worth the price: Denis Brian, *Einstein: A Life* (1996); Albrecht Fölsing, *Albert Einstein: A Biography* (1997); and Jürgen Neffe, *Einstein: A Biography* (2007). But one should not discount older biographies just because of their vintage. Three of my favorites have aged like fine wine. They are: Ronald W. Clark, *Einstein: The Life and Times* (1971); Philipp Frank, *Einstein: His Life and Times* (1947); and Banesh Hoffmann and Helen Dukas, *Albert Einstein, Creator and Rebel* (1972). Lest we forget, Einstein wrote his own intellectual autobiography: "Autobiographical Notes" (1949). Should that not be at the top of everyone's list?

Einstein in His Own Words

One telling measure of Einstein's talents is that he was a superb writer. His technical papers, those written after he hit his stride in 1905, are models of clarity. Even the nonspecialist should sample them, not letting the excuses of lacking the technical vocabulary or the mathematical facility get in the way of appreciating rigorous science presented in well-crafted prose. Many of Einstein's more popular essays on philosophy, religion, biography, and politics achieve a level of elegance not always seen in writings by scientists. Lucid like the scientific essays, Einstein's popular essays are famous for their well-turned phrases, their effective use of imagery, and the passion that animates even the more factual subjects. Everyone interested in Einstein will want to read more than a few.

Eventually, all of Einstein's published writings and nearly all of his unpublished manuscripts and private correspondence will be available in the series *The Collected Papers of Albert Einstein*, which is published by Princeton University Press and is produced by the Einstein Papers Project, located at Caltech and currently directed by Professor Diana Kormos Buchwald. As of 2008, 10 volumes are in print, covering the period from Einstein's birth through 1920, for the correspondence, and 1921, for the writings. Each volume presents Einstein's papers or letters in the original language, and in facsimile in the case of published papers. Extensive editorial notes and introductory notes (in English) put the letters and papers in context. Each volume in the *Collected Papers* is accompanied by a "pony," a paper-bound companion volume that provides serviceable English translations for all letters, manuscripts, and papers that do not appear in English in the main volumes (editorial notes and introductions will only be found in the main volumes, however). That means that, as the *Collected Papers* series grows, more or less everything that Einstein wrote will be available in English. Copies of all volumes in the *Collected Papers* should be available in any good academic or public library. For more information about the *Collected Papers*, visit the Einstein Papers Project website: http://www.einstein.caltech.edu/.

Those who wish to see and read original manuscript material are welcome to do so at the repositories for the Einstein Archives. Currently three are open to scholars: at the Hebrew University and National Library in Jerusalem, at Princeton University, and at Boston University (both of the latter two institutions having at one time housed the Einstein Papers Project). Gradually, more and more archival material is being made available electronically through the Einstein Archives Online: http://www.alberteinstein.info/. There you will already find high-quality digital images of such treasures as Einstein's own student notebooks from his physics lectures with H. F. Weber at the ETH and the travel diaries Einstein kept while on his trip to Japan in 1922 to 1923 and his third trip to Caltech in the spring of 1933.

Otherwise, many of Einstein's writings are in print. Perhaps the best place to start is with the rich collection of mostly popular essays found in *Ideas and Opinions* (1954—but always in print). For an introduction to relativity, it's hard to improve upon Einstein's own popular book, *Relativity: The Special and General Theory, A Popular Exposition*, which first appeared in English in 1920 and has been in print ever since. Also hard to top is Einstein's technical introduction to relativity, based on his 1921 Princeton lectures, *The Meaning of Relativity*, which first appeared in English in 1922, went through five editions in Einstein's lifetime, and is also still in print. The history of physics coauthored by Einstein and his collaborator Leopold Infeld, *The Evolution of Physics* (1938, but still in print) is intended for the nonspecialist and compares well to histories written by specialist historians of science. A real treasure is the Einstein volume in the Library of Living Philosophers series, edited by Paul Schillp, *Albert Einstein: Philosopher-Scientist* (1949 and continuously in print since then). It opens with Einstein's own "Autobiographical Notes." Twenty-five critical essays on Einstein's work are then

followed by Einstein's "Replies to Criticisms," which all by itself stands as one of Einstein's more important papers. The volume concludes with a comprehensive bibliography of Einstein's published writings.

Various bits of Einstein's correspondence are also available independent of the *Collected Papers*. One is the interesting collection of letters to an old Olympia Academy friend, *Letters to Solovine, 1906–1955* (2000). Still more compelling is *The Born-Einstein Letters* (2004), edited by Einstein's friend, physicist Max Born. Spanning four decades and two continents, these letters tell the story of three lives (Max Born's wife, Hedwig, is one of the correspondents) and the story of physics during an unusually tumultuous period. Einstein's correspondence with his close personal friend Michele Besso was published in the original German and French a long time ago: *Albert Einstein Correspondance avec Michele Besso 1903–1955* (1972), edited by Pierre Speziali. Copies are not easy to find, and an English translation was never produced, but if you can read German and French, the hard work to find the book will be repaid.

Lastly, Einstein was justly famous for the brief quip and the trenchant one-liner. No library is complete without a copy of Alice Calaprice's compendium, *The New Quotable Einstein* (2005).

Einstein in the Words of Others

The secondary literature on Einstein is immense, far too large for one to make even a pretense of surveying it in a bibliography of this sort. But following out the references in the books and papers that are cited below will quickly lead one deeply into the heart of both popular and scholarly writings on Einstein. I will, however, recommend one specific place to look, namely, the *Einstein Studies* series, published by Birkhäuser and coedited by myself and John Stachel, the founding editor of *The Collected Papers of Albert Einstein*. As of 2008, the *Einstein Studies* series comprised 11 volumes of mostly scholarly work on Einstein and related topics, among them the collection *Einstein: The Formative Years, 1879–1909* (2000) and Stachel's collected papers, *Einstein from "B" to "Z,"* both of which appear in citations found elsewhere in this bibliography. As with Einstein's *Collected Papers*, volumes in the *Einstein Studies* series should be readily available in university libraries and better public libraries. More information about the series can be found at the website of Birkhäuser's parent company, Springer: http://www.springer.com.

Suggested Reading:

Baggott, Jim. *Beyond Measure: Modern Physics, Philosophy, and the Meaning of Quantum Theory*. Oxford: Oxford University Press, 2004. Very technical. Introduction to the physics of quantum and to the major alternative interpretations.

Beller, Mara. *Quantum Dialogue: The Making of a Revolution*. Chicago: University of Chicago Press, 1999. A richly detailed history and analysis of debates about the interpretation of quantum mechanics, emphasizing the period from the late 1920s through the early to mid-1930s and the rise of Niels Bohr's so-called Copenhagen interpretation, which features the principle of complementarity.

Bernstein, Jeremy. *Albert Einstein and the Frontiers of Physics*. New York: Oxford University Press, 1996. An accessible introduction for the nonspecialist.

———. *Secrets of the Old One: Einstein, 1905*. New York: Copernicus, 2005. Nontechnical, accessible to the nonspecialist; focuses on Einstein's "miracle year."

Beyerchen, Alan. *Scientists under Hitler: Politics and the Physics Community in the Third Reich*. New Haven: Yale University Press, 1977. The definitive study of Nazism's impact on German science.

Bohr, Niels. "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?" *Physical Review* 48: 696–702. Bohr's reply to the classic EPR paper.

Born, Max, ed. *The Born-Einstein Letters: Friendship, Politics and Physics in Uncertain Times*. New York: Macmillan, 2004. A fascinating record of a personal and professional friendship, this new printing of the correspondence between Einstein, Max Born, and Hedwig Born features a new introduction by Kip Thorne and Diana Kormos Buchwald, editor of *The Collected Papers of Albert Einstein*, that provides helpful historical and scientific context.

Brian, Denis. *Einstein: A Life*. New York: J. Wiley, 1996. One of the better recent comprehensive biographies.

Calaprice, Alice, ed. *The New Quotable Einstein*. Enlarged commemorative edition. Princeton, NJ: Princeton University Press, 2005. The definitive collection of Einstein's one-liners and short remarks, both serious and humorous.

Clark, Ronald W. *Einstein: The Life and Times*. New York: World, 1971. The best of the older generation of comprehensive biographies.

Einstein, Albert. "Atomic War or Peace." In *Ideas and Opinions*, 118–31. New York: Bonanza Books, 1954. Reprinting, with some editorial changes, of the 1941 and 1947 articles in the *Atlantic Monthly* based on an interview by Raymond Swing.

———. "Autobiographical Notes." In *Albert Einstein: Philosopher-Scientist*, edited by Paul Arthur Schilpp. Evanston, IL: Library of Living Philosophers, 1949. (3rd ed., LaSalle, IL: Open Court, 1970, 1–94.) Actually written a few years earlier, around 1946, this is Einstein's only extended discussion of his own life, with an emphasis on his intellectual development and his work in physics.

———. "Geometry and Experience." In *Ideas and Opinions*, 232–46. New York: Bonanza Books, 1954. Reprinting of a lecture given originally in Berlin in 1921. Einstein's most important discussion of the philosophical issues concerning general relativity's implications regarding the geometry of space-time.

———. *Ideas and Opinions.* New York: Bonanza Books, 1954. The most comprehensive collection of Einstein's essays on a wide array of scientific and nonscientific topics. Still in print and sure to be so for a long time.

———. *Letters to Solovine, 1906–1955*. New York: Citadel, 2000. Correspondence between Einstein and one of his friends from the Olympia Academy.

———. *The Meaning of Relativity: Including the Relativistic Theory of the Non-symmetric Field*. 5th ed. Translated by Edwin P. Adams. Princeton, NJ: Princeton University Press, 2004. Einstein's own technical introduction to relativity, based on a series of four lectures delivered at Princeton University in 1921. First published in English in 1922, the 2004 printing of the 5th edition carries a helpful introduction by Brian Greene.

———. "On the Method of Theoretical Physics." In *Ideas and Opinions*, 270–76. New York: Bonanza Books, 1954. Reprinting of Einstein's 1933 Herbert Spencer lecture in London. An important discussion of the roles of reason and experience in science, with an emphasis on the role of mathematical simplicity in theory choice.

———. "Physics and Reality." In *Ideas and Opinions*, 290–323. New York: Bonanza Books, 1954. Reprinting of Einstein's 1936 essay, his most extended statement of his philosophy of science, originally published in the *Journal of the Franklin Institute*.

———. *Relativity: The Special and General Theory, A Popular Exposition*. Translated by Robert W. Lawson. New York: Plume, 2006. Einstein's own popular introduction, first published in German in 1917, then in English in 1920, and since reprinted many times. This new edition includes helpful commentary by Robert Geroch and an introduction by Roger Penrose.

———. "Science and Religion." In *Ideas and Opinions*, 41–49. New York: Bonanza Books, 1954. Reprinting of a 1939 lecture at the Princeton Theological Seminary.

———. "Why Socialism?" In *Ideas and Opinions*, 151–59. New York: Bonanza Books, 1954. Reprinting of the widely read essay first published in the *Monthly Review* in 1949.

Einstein, Albert, and Leopold Infeld. *The Evolution of Physics: From Early Concepts to Relativity and Quanta*. New York: Simon & Schuster, 2007. Reprinting of the classic 1938 book by Einstein and his assistant and collaborator Infeld, with a new introduction by Walter Isaacson. As good a historical and pedagogical introduction to the physics of the past 400 years as one could want. And why not get it from the master himself? (Though the book was written mainly by Infeld.)

Einstein, Albert, Boris Podolsky, and Nathan Rosen. "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?" *Physical Review* 47 (1935), 777–80. The famous EPR paper that seeks to prove the incompleteness of quantum mechanics.

Everdell, William R. *The First Moderns: Profiles in the Origins of Twentieth-Century Thought*. Chicago: University of Chicago Press, 1997. An insightful and wide-ranging exploration of modernity and Modernism in culture; pays special attention to relations between art and literature on the one hand and science on the other.

Fine, Arthur. "Einstein's Realism." In *The Shaky Game: Einstein, Realism, and the Quantum Theory*, 86–111. Chicago: University of Chicago Press, 1986. A superbly insightful essay about Einstein's position in the debate over realist versus instrumentalist interpretations of scientific theories.

Fölsing, Albrecht. *Albert Einstein: A Biography*. New York: Viking, 1997. A respectable recent biography.

Frank, Philipp. *Einstein: His Life and Times*. Translated by George Rosen. New York: Alfred A. Knopf, 1947. Reprint, Cambridge, MA: Da Capo, 2002. Though dated, still one of the very best Einstein biographies, by a longtime friend of Einstein's who enjoyed access to Einstein while writing the biography.

———. *Relativity: A Richer Truth*. Boston: Beacon Press, 1950. A defense of relativity (and Einstein) against the charge that relativity in physics entails relativism in morals.

Frayn, Michael. *Copenhagen*. New York: Anchor Books, 2000. A play examining the morality and politics of physicists' involvement in the development of the atomic bomb, based on a famous wartime meeting between Niels Bohr and Werner Heisenberg in Copenhagen—then under German occupation—in September 1941. One should also seek out either of the two stagings available on DVD. The *PBS Hollywood Presents* version starring Stephen Rea, Daniel Craig, and Francesca Annis has the advantage of having been filmed at the old Bohr estate in Copenhagen.

Galison, Peter. *Einstein's Clocks, Poincaré's Maps: Empires of Time*. New York: W. W. Norton, 2003. A highly readable history that situates the birth of relativity in a broad historical and cultural context, paying special attention to contemporary technical developments in chronometry.

Galison, Peter, Gerald Holton, and Silvan S. Schweber, eds. *Einstein for the 21st Century: His Legacy in Science, Art, and Modern Culture*. Princeton, NJ: Princeton University Press, 2008. A delightful collection of recent essays on many aspects of Einstein's life, work, and legacy.

Geroch, Robert. *General Relativity from A to B*. Chicago: University of Chicago Press, 1978. A nonmathematical but surprisingly rigorous introduction based on the use of space-time diagrams. Originally prepared for a general science course for nonscience majors at the University of Chicago.

Goenner, Hubert. "On the History of Unified Field Theories." *Living Reviews in Relativity* 7 (2004): 2. Online at: http://www.livingreviews.org/lrr-2004-2. A very thorough history, an important supplement or complement to Vizgin's history.

Graff, Karl Wolfgang. "The Automatic 'Concrete People's Refrigerator' CITOGEL by Albert Einstein and Leo Szilard." In *Albert Einstein, Chief Engineer of the Universe: One Hundred Authors for Einstein*. Edited by Jürgen Renn, 238–41. Berlin: Wiley-VCH, 2005. An informative historical note about the Einstein-Szilard refrigerator patent.

Gray, Jeremy. *Ideas of Space: Euclidean, Non-Euclidean, and Relativistic*. 2nd ed. Oxford: Oxford University Press, 1989. An accessible and comprehensive overview for the nonspecialist. Only high school mathematics is assumed.

Hoffmann, Banesh, and Helen Dukas. *Albert Einstein, Creator and Rebel*. New York: Viking, 1972. Still one of the best Einstein biographies, by Einstein's longtime scientific collaborator Hoffmann and his longtime private secretary Dukas.

Holton, Gerald. "Mach, Einstein, and the Search for Reality." In *Thematic Origins of Scientific Thought: Kepler to Einstein*, 219–59. Cambridge, MA: Harvard University Press, 1973. Reprinting of a classic and widely cited study of the development of Einstein's philosophy of science, first published in 1968 in *Daedalus*.

Hooper, Dan. *Dark Cosmos: In Search of Our Universe's Missing Mass and Energy*. New York: Smithsonian Books/HarperCollins, 2006. An accessible account of recent work on dark matter and dark energy for the nonspecialist.

Howard, Don. "Albert Einstein as a Philosopher of Science." *Physics Today* 58, no. 11 (2005): 34–40. A not overly technical overview of major themes in Einstein's thinking about the philosophy of science.

———. "Einstein on Locality and Separability." *Studies in History and Philosophy of Science* 16 (1985): 171–201. A detailed and somewhat technical discussion of the development of Einstein's thinking about the role of the separability principle in arguing for the incompleteness of quantum mechanics from the 1935 EPR paper through the mid-1950s.

———. "'Nicht sein kann was nicht sein darf,' or the Prehistory of EPR, 1909–1935: Einstein's Early Worries about the Quantum Mechanics of Composite Systems." In *Sixty-Two Years of Uncertainty: Historical, Philosophical, and Physical Inquiries into the Foundations of Quantum Mechanics*. Edited by Arthur I. Miller, 61–111. New York: Plenum, 1990. A detailed and somewhat technical discussion of Einstein's thinking about entanglement, separability, wave-particle duality, and the completeness of quantum mechanics from 1945 up to the publication of the EPR paper in 1935.

Howard, Don, and John J. Stachel, eds. *Einstein: The Formative Years, 1879–1909*. Boston: Birkhäuser, 2000. A collection of essays on various topics concerning Einstein's early years, including both his physics and biographical topics, such as his childhood reading and his physics education at the ETH.

Hu, Danian. *China and Albert Einstein: The Reception of the Physicist and His Theory in China, 1917–1979.* Cambridge, MA: Harvard University Press, 2005. A fascinating history of Einstein's impact on Chinese science, culture, and politics.

Hughes, Thomas P. "Einstein the Inventor." *American Heritage of Invention and Technology* 6, no. 3 (Winter 1991), 34–39. Lively and informative. One of few articles that focuses on this crucial side of Einstein's life and work.

Isaacson, Walter. *Einstein: His Life and Universe*. New York: Simon & Schuster, 2007. The best of the new generation of comprehensive Einstein biographies. But it is weak on the physics, for which one must turn to a source like Abraham Pais's intellectual biography.

Jammer, Max. *The Conceptual Development of Quantum Mechanics*. New York: McGraw-Hill, 1966. Long out of print, but still available in libraries and from used book dealers and still the best single-volume technical history of quantum mechanics. There was a 1989 second edition published under the auspices of the American Institute of Physics, but copies of that are hard to find.

———. *Einstein and Religion: Physics and Theology*. Princeton, NJ: Princeton University Press, 1999. An enjoyable and profitable read. The only book to have addressed this important aspect of Einstein's thought.

———. *The Philosophy of Quantum Mechanics: The Interpretations of Quantum Mechanics in Historical Perspective*. New York: Wiley, 1974. Like his book on the history of quantum mechanics, long out of print but still available in libraries and from used book dealers and still the best historical study of the interpretation of quantum mechanics.

Jerome, Fred. *The Einstein File: J. Edgar Hoover's Secret War against the World's Most Famous Scientist*. New York: St. Martin's Press, 2002. A thorough history and analysis of the FBI's campaign of surveillance directed against Einstein, based mainly on the FBI's own records, obtained through the Freedom of Information Act.

Jerome, Fred, and Rodger Taylor. *Einstein on Race and Racism*. New Brunswick, NJ: Rutgers University Press, 2005. The only book to date to examine Einstein's extensive involvement with civil rights and his personal relationships with members of the African American community in Princeton.

Jungk, Robert. *Brighter than a Thousand Suns: A Personal History of the Atomic Scientists*. New York: Harcourt Brace, 1958. Reprint, Harvest, 1970. Dated, but still my favorite for classroom use, and still in print.

Kaku, Michio. *Einstein's Cosmos: How Albert Einstein's Vision Transformed Our Understanding of Space and Time*. New York: W. W. Norton, 2004. A highly readable, lively, popular overview of Einstein's work in physics.

Kennefick, Daniel. *Traveling at the Speed of Thought: Einstein and the Quest for Gravitational Waves*. Princeton, NJ: Princeton University Press, 2007. A careful historical study of the genesis of the idea of gravity waves and of later attempts to detect gravitation waves, up to the ongoing LIGO experiment.

Kragh, Helge. *Cosmology and Controversy: The Historical Development of Two Theories of the Universe*. Princeton, NJ: Princeton University Press, 1996. A history of cosmology in the 20th century focusing on the debate between steady-state and big bang cosmologies.

———. *Quantum Generations: A History of Physics in the Twentieth Century*. Princeton, NJ: Princeton University Press, 1999. The best general history of 20th-century physics currently available. Not overly mathematical.

Levenson, Thomas. *Einstein in Berlin*. New York: Bantam, 2003. Combines history and biography to illuminate the middle part of Einstein's life and career.

Lindley, David. *Uncertainty: Einstein, Heisenberg, Bohr, and the Struggle for the Soul of Science*. New York: Doubleday, 2007. A historically organized, nontechnical survey of debates about the interpretation of quantum mechanics.

Miller, Arthur I. *Einstein, Picasso: Space, Time, and the Beauty That Causes Havoc*. New York: Basic Books, 2001. A joint biography of the physicist and the painter, with a focus on the theme of the modern.

Nathan, Otto and Heinz Norden, eds. *Einstein on Peace*. New York: Simon & Schuster, 1960. Assembled under the direction of Einstein's close friend and literary executor Otto Nathan. Currently out of print but available in libraries and on the used book market in either the original edition or several reprint editions. Well worth the effort to locate a copy.

Neffe, Jürgen. *Einstein: A Biography*. New York: Farrar, Straus, and Giroux, 2007. One of the newest comprehensive biographies. A bit unusual in its thematic mode of organization.

Overbye, Dennis. *Einstein in Love: A Scientific Romance*. New York: Viking, 2000. An Einstein biography focusing especially on the relationship between Albert and Mileva.

Pais, Abraham. *"Subtle is the Lord …": The Science and the Life of Albert Einstein*. New York: Oxford University Press, 1983. The definitive intellectual biography of Einstein. To be corrected on some few points by more recent scholarship but still, by far, the most thorough and careful study of Einstein's work in physics. Requires a significant technical background.

Parker, Barry. *Einstein's Dream: The Search for a Unified Theory of the Universe*. New York: Basic Books, 2001. An accessible introduction to the program of unification in the physics focusing on Einstein and the earlier 20th century.

Regis, Edward. *Who Got Einstein's Office? Eccentricity and Genius at the Institute for Advanced Study*. Reading, MA: Addison-Wesley, 1987. A somewhat breezy and, some think, insufficiently reverent history of the Institute for Advanced Study. But a good source of information about the intellectual world that Einstein inhabited at the Institute.

Renn, Jürgen, ed. *The Genesis of General Relativity: Sources and Interpretations*. Dordrecht, Netherlands: Springer, 2007. This massive four-volume collection represents the product of more than a decade of collaborative work by a group of scholars associated with the Max-Planck Institute for History of Science in Berlin. A model of careful scholarship, this will long be the definitive history of the development of general relativity.

Renn, Jürgen, and Robert J. Schulmann, eds. *Albert Einstein-Mileva Marić: The Love Letters*. Translated by Shawn Smith. Princeton, NJ: Princeton University Press, 2000. A nice edition and translation of the letters between Einstein and his future first wife during the period of their romance and the birth of their illegitimate daughter, Lieserl.

Rhodes, Richard. *Dark Sun: The Making of the Hydrogen Bomb*. New York: Simon & Schuster, 1995. As with Rhodes's book on the atomic bomb, still the definitive history.

———. *The Making of the Atomic Bomb*. New York: Simon & Schuster, 1986. Still the definitive history, densely packed with detail but lacking some information from both Soviet and U.S. sources that was declassified after the book's publication.

Rosenkranz, Ze'ev. "Albert Einstein and the German Zionist Movement." In *Albert Einstein, Chief Engineer of the Universe: One Hundred Authors for Einstein*, edited by Jürgen Renn, 302–7. Berlin: Wiley-VCH, 2005. Very helpful background on this important political engagement of Einstein's.

Rowe, David E., and Robert Schulmann, eds. *Einstein on Politics: His Private Thoughts and Public Stands on Nationalism, Zionism, War, Peace, and the Bomb*. Princeton, NJ: Princeton University Press, 2007. A superb collection of Einstein's own writings together with very helpful historical commentary. Strongly recommended.

Sayen, Jamie. *Einstein in America: The Scientist's Conscience in the Age of Hitler and Hiroshima*. New York: Crown, 1985. Focuses on Einstein's political involvements during his 22 years in the United States. The author was helped by interviews with Einstein's stepdaughter Margot.

Schilpp, Paul Arthur, ed. *Albert Einstein: Philosopher-Scientist*. Evanston, IL: Library of Living Philosophers, 1949. (3rd ed., LaSalle, IL: Open Court, 1970). An important collection of essays on Einstein that also includes Einstein's replies and Einstein's intellectual autobiography. Still in print.

Schweber, Silvan S. *In the Shadow of the Bomb: Oppenheimer, Bethe, and the Moral Responsibility of the Scientist*. Princeton, NJ: Princeton University Press, 2000. Parallel biographies of Bethe and Oppenheimer with an emphasis on their contrasting approaches to the question of the scientist's moral responsibilities.

Smolin, Lee. *The Trouble with Physics: The Rise of String Theory, the Fall of a Science, and What Comes Next*. Boston: Houghton Mifflin, 2006. A somewhat argumentative, critical analysis of the contemporary state of affairs in the area of physics concerned with attempts to unify quantum mechanics and general relativity in what is called "quantum gravity."

Speziali, Pierre, ed. *Albert Einstein Correspondance avec Michele Besso 1903–1955*. Paris: Hermann, 1972. A vast and rich correspondence between Einstein and his closest personal friend. Sadly, long out of print, very hard to find, and never translated into English. But for those with the language skills and the patience to find a copy, this collection is well worth the effort.

Stachel, John. "Einstein and the American Left." In *Albert Einstein, Chief Engineer of the Universe: One Hundred Authors for Einstein*, edited by Jürgen Renn, 354–57. Berlin: Wiley-VCH, 2005. One of the few articles focusing on Einstein's relations with the American left, by an author who knows this bit of history better than just about anyone else.

———. "Einstein's Jewish Identity." In *Einstein from "B" to "Z,"* 57–83. Boston: Birkhäuser, 2002. Very informative overview, part of a collection of Stachel's writings on Einstein, all of which are strongly recommended.

———, ed. *Einstein's Miraculous Year: Five Papers that Changed the Face of Physics*. Princeton, NJ: Princeton University Press, 1998. Assembled by the founding editor of *The Collected Papers of Albert Einstein*, this reprinting of Einstein's "miracle year" papers includes extensive introductions providing analysis and historical context.

Stachel, John, et al., ed. *The Collected Papers of Albert Einstein*. Vol. 1, *The Early Years, 1879–1902*. Translated by Anna Beck. Consultant Peter Havas. Princeton, NJ: Princeton University Press, 1987.

Stern, Fritz. *Einstein's German World*. Princeton, NJ: Princeton University Press, 1999. A collection of essays by a leading specialist on 20th-century German history. Einstein is the thread linking together essays on figures like Chaim Weizmann, Walther Rathenau, Fritz Haber, and Max Planck.

Vargish, Thomas, and Delo E. Mook. *Inside Modernism: Relativity Theory, Cubism, Narrative*. New Haven: Yale University Press, 1999. A focused look at connections among relativity, art, and literature by a physicist (Mook) and a specialist in English literature (Vargish).

Vizgin, Vladimir P. *Unified Field Theories in the First Third of the 20th Century*. Translated by Julian Barbour. Basel, Switzerland: Birkhäuser, 1994. The definitive, technical history of early 20th century attempts at a unified field theory.

Wald, Robert M. *Space, Time, and Gravity: The Theory of the Big Bang and Black Holes*. 2nd ed. Chicago: University of Chicago Press, 1992. A modestly technical but still accessible introduction to the physics of relativistic cosmology.

Wang, Jessica. *American Science in an Age of Anxiety: Scientists, Anticommunism, & the Cold War.* Chapel Hill: University of North Carolina Press, 1999. A careful study of the interactions between science and politics in the United States in the immediate post–World War II period.

Weinberg, Steven. *Dreams of a Final Theory*. New York: Pantheon, 1992. A lucid and not overly technical discussion by a prominent theoretical physicist of the ideal of unification in physics at the end of the 20th century.

Will, Clifford M. *Was Einstein Right? Putting General Relativity to the Test*. 2nd ed. New York: Basic Books, 1993. A not overly technical survey of the history of tests of general relativity. Very readable. Even the second edition is now a bit dated, but an update, "The Confrontation between General Relativity and Experiment," can be found at the *Living Reviews in Relativity* website: http://relativity.livingreviews.org/Articles/lrr-2006-3.

Winteler-Einstein, Maja. "Albert Einstein—A Biographical Sketch." In *The Collected Papers of Albert Einstein.* Vol. 1, *The Early Years, 1879–1902*, edited by John Stachel et al., translated by Anna Beck, consultant Peter Havas, xv–xxii. Princeton, NJ: Princeton University Press, 1987. English translation of the German original, which appears (with extensive annotations in English) on pp. xlviii-lxvi. This is the only available source of biographical information on Einstein's earliest years from a member of his immediate family. Well worth the effort to track down in a library or through the Internet.

Wolff, Barbara. "Albert Einstein and Music." In *Albert Einstein, Chief Engineer of the Universe: One Hundred Authors for Einstein*, edited by Jürgen Renn, 250–55. Berlin: Wiley-VCH, 2005. The most careful and informed essay ever written on Einstein and music.

Zackheim, Michele. *Einstein's Daughter: The Search for Lieserl*. New York: Riverhead Books, 1999. Reads much like a detective story about the author's own, ultimately fruitless, investigations in Serbia. A good read, but too much ungrounded speculation in place of hard facts.